

# Two step FVE method

A numerical modeling technique designed for error insight

1D & 2D Shallow water equations

J. Mooiman

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# Contents

<b>List of Tables</b>	<b>7</b>	
<b>List of Figures</b>	<b>8</b>	
<b>List of Symbols</b>	<b>11</b>	
<b>List of To Do's</b>	<b>12</b>	
<b>Introduction</b>	<b>13</b>	
<b>1</b>	<b>Introduction</b>	<b>14</b>
<b>2</b>	<b>Two-step numerical modeling, error minimizing</b>	<b>17</b>
<b>3</b>	<b>Time integration scheme</b>	<b>19</b>
3.1	Fully implicit time integration by adding an iteration process	19
3.1.1	Pseudo time stepping	21
3.2	Jacobians	21
3.2.1	Non-linear term, product	22
3.2.2	Non-linear term, quotient	23
3.2.3	Non-linear term, product and quotient	23
3.2.4	Terms with an operator	24
<b>4</b>	<b>1-D Space discretization</b>	<b>26</b>
4.1	Finite volume approach	26
4.1.1	Quadrature rule, source term	26
4.1.1.1	1-point Gauss	27
4.1.1.2	2-point Gauss	28
4.1.2	Boundary conditions	28
4.2	Regularization of artificial viscosity $\Psi$	30
4.3	Regularization of given function	31
4.3.1	Determination of artificial smoothing coefficient $\Psi$	33
4.3.2	Step function (Heaviside function)	33
4.3.3	Small and a large gradient in the data set	36
4.4	Compatible initialization in one dimension	38
4.5	Compatible initialization in two dimensions	39
<b>1D Wave</b>	<b>40</b>	
<b>5</b>	<b>Towards the shallow water equations</b>	<b>41</b>

5.1	0-D Source/sink term	42
5.1.1	Air pollution	42
5.1.2	Brusselator	45
5.2	1-D Advection-diffusion equation	46
5.2.1	Not strictly positive constituent	46
5.2.2	Strictly positive constituent	48
5.3	1-D Wave equation	49
5.3.1	Discretizations continuity equation	50
5.3.1.1	Time derivative	50
5.3.1.2	Mass flux	51
5.3.2	Discretizations momentum equation	51
5.3.2.1	Time derivative	51
5.3.2.2	Pressure term	52
5.3.2.3	Convection	53
5.3.2.4	Bed shear stress	53
5.3.2.5	Viscosity	54
5.3.3	Discretizations at boundary	55
5.3.3.1	Essential boundary condition	56
5.3.3.2	Natural boundary condition	57
<b>6</b>	<b>Numerical experiments</b>	<b>62</b>
6.1	0-D, sources and sinks	62
6.1.1	Air pollution	62
6.1.2	Brusselator	63
6.2	1-D Advection equation	65
6.2.1	Transport of a constant constituent at the boundary	65
6.2.2	Transport of a time-dependent constituent at the boundary	67
6.2.3	Transport of a wave package inside the domain	68
6.2.4	Transport of strictly positive constituent	69
6.3	1-D Advection-diffusion equation	70
6.3.1	Outflow boundary layer	71
6.3.2	Interface problem	73
6.4	1-D Wave equation	74
6.4.1	Gaussian hump	74
6.4.2	Weir	75
<b>2D Wave</b>	<b>78</b>	
<b>7</b>	<b>2D Shallow water equations</b>	<b>79</b>
7.1	Space discretization, structured grid	81
7.1.1	Discretization continuity equation	81

7.1.1.1	Time derivative	82
7.1.1.2	Mass flux	83
7.1.2	Discretizations momentum equations	84
7.1.2.1	Time derivative	84
7.1.2.2	Pressure term	84
7.1.2.3	Convection	86
7.1.2.4	Bed shear stress	87
7.1.2.5	Viscosity	89
7.1.3	Discretization at boundary	90
7.1.3.1	Essential boundary condition	92
7.1.3.2	Natural boundary condition	95
7.1.4	Discretization at corner	101
<b>8</b>	<b>2D Wave numerical experiments</b>	<b>102</b>
8.1	Gaussian hump	102
8.1.1	Gaussian hump	102
8.1.2	Gaussian hump, reflection	103
<b>References</b>		<b>105</b>
<b>Appendices</b>		<b>107</b>
<b>A</b>	<b>Curvilinear coordinate transformation</b>	<b>108</b>
A.1	Transforming the terms	110
A.1.1	Convection term	111
A.1.2	Viscosity term	112
A.1.2.1	For a cartesian grid	114
A.2	Transformed 2D Shallow Water Equations	115
A.3	Jacobians of the flux and source terms	118
A.3.1	Continuity Flux Jacobians	119
A.3.2	Convective Flux Jacobians	119
A.3.3	Viscous Flux Jacobians	120
<b>B</b>	<b>Error estimation</b>	<b>124</b>
B.1	Numerical error	125
B.2	Determining the factor $c_\Psi$	127
B.3	$L^1$ -norm for the functions $\tilde{u}$ , $\bar{u}$ and $u_{given}$	127
<b>C</b>	<b>Diagonalise 1-D wave equation with convection</b>	<b>130</b>
<b>D</b>	<b>Error function needed to regularize the artificial viscosity</b>	<b>132</b>
<b>E</b>	<b>Linearization in time</b>	<b>135</b>

E.1	Viscosity term	135
<b>F</b>	<b>Regularization of a two dimensional given function <math>u_{giv}</math></b>	<b>137</b>
F.1	Discretization	137
F.2	Determination of artificial smoothing coefficient $\Psi$	140

# List of Tables

6.1	Stability for different time integrators	63
6.2	Stability of different time integrators for the Brusselator.	64
B.1	Several typical values for numerical accuracy, $c_\psi$ and number of nodes per wavelength ( $N$ ), the highlighted line is set as default.	127

# List of Figures

2.1	Graphical presentation of the error-minimizing two step method	17
4.1	Water body (blue area), finite volumes (green boxes), computational points (open dots), virtual computational points (black dots), boundary points (open squares) are at $i = 1$ (west boundary) and $i = I$ (east boundary).	26
4.2	Illustration of the 1-point Gauss integration method of a linear functions.	27
4.3	Illustration of the 1-point and 2-point Gauss integration method of a quadratic function.	28
4.4	Two dimensional example of a lot of data points per grid cell. The data points are used to compute the integral at the right hand side of equation (4.28).	32
4.5	Step function to be estimated. The thin green vertical lines indicate the borders of the finite volumes.	34
4.6	As seen from this figures the function defined on the grid nodes does not see the exact location of the step. Both functions through the grid nodes have the same profile, but the step is at another location.	34
4.7	Step function approximated by a piecewise linear function (red line with dots at the nodes), $c_\Psi = 0$ , $\Delta x = 100$ [m] and $\Psi = 0$ . The thin green vertical lines indicate the borders of the finite volumes.	35
4.8	Step function approximated by a piecewise linear function (red line with dots at the nodes), $c_\Psi = 4$ , $\Delta x = 100$ [m] and $\Psi = 40000$ . The thin green vertical lines indicate the borders of the finite volumes.	35
4.9	Step function approximated by a piecewise linear function (red line with dots at the nodes), $c_\Psi = 4$ , $\Delta x = 50$ [m] and $\Psi = 10000$ . The thin green vertical lines indicate the borders of the finite volumes.	36
4.10	Large and small gradients in given function.	36
4.11	Initial guess ( $c_\Psi = 4$ , $\Delta x = 50$ [m])	37
4.12	Regularization coefficient increased to 16 ( $c_\Psi = 16$ , $\Delta x = 50$ [m])	37
4.13	Grid size decreased to 25 [m] ( $c_\Psi = 4$ , $\Delta x = 25$ [m])	37
4.14	Illustration of compatible quadratic function	38
5.1	Definition sketch of water level ( $\zeta$ ), bed level ( $z_b$ ) and total water depth ( $h$ )	41
5.2	Definition of the grid to solve the 1D-advection equation	46
6.1	Air pollution experiment: $O$ , $N_2$ , $NO$ and $O_3$	62
6.2	Brusselator experiment: $\Delta t = 0.001$ [s]	63
6.3	Brusselator experiment: $\Delta t = 0.1, 0.5$ [s]	64

6.4	Brusselator experiment: $\Delta t = 1.0, 5.0$ [s]	64
6.5	Spurious waves at $t = 3600$ [s]. Range from $1 \pm 8 \times 10^{-9}$ .	66
6.6	Time-series for several stations in the model, showing the transition behavior between the initial situation and the time-independent solution.	66
6.7	Time-series for several stations in the model, showing the transition behavior between the initial situation and the time-independent solution.	67
6.8	Compatible initial condition of the wave package. Blue: Initial condition when $\Delta x = 5$ [m], Black: Initial condition when $\Delta x = 50$ [m].	68
6.9	Wave package experiment	69
6.10	Map results for different values of the advection velocity (thus Péclet number). The graphs with an asterix represent results with a cell Péclet number larger than two. Black: $Pe = 1.0$ ; Blue: $Pe = 1.9$ , Green: $Pe = 2.1$ ; Cyan: $Pe = 5.0$ .	72
6.11	Map results for the used artificial diffusion $\Psi$ . Black: $Pe = 1.0$ ; Blue: $Pe = 1.9$ , Green: $Pe = 2.1$ ; Cyan: $Pe = 5.0$ .	72
6.12	Map results for the used cell Péclet number. Black: $Pe = 1.0$ ; Blue: $Pe = 1.9$ , Green: $Pe = 2.1$ ; Cyan: $Pe = 5.0$ .	73
6.13	Map results for different values of the Péclet number.	74
6.14	Weir experiment: water level and bed level	77
6.15	Weir experiment: Artificial viscosity $\Psi$ and Froude number	77
7.1	Definition sketch of water level ( $\zeta$ ), bed level ( $z_b$ ) and total water depth ( $h$ )	79
7.2	Definition of the grid to solve the 2D-shallow water equations in the interior area	81
7.3	Definition of the grid to solve the 2D-shallow water equations at the boundary	91
7.4	Essential boundary condition, dotted lines indicate the border of the control volumes.	92
7.5	Natural boundary condition ( $i = 1$ ), dotted lines indicate the border of the control volumes. The diamonds indicate the quadrature points.	95
7.6	Layout of the essential boundary (blue-line) and natural boundary (orange-line) in 2-dimensions on a structured grid at the upper-left corner. No line integrals are performed in the corner, so just the red-dot.	101
8.1	Schematization area: $[-6000, 6000]x[-6000, 6000]$ [m] and $[-6000, 6000]x[-3000, 3000]$ [m]. The observation points at $y = 3000$ [m] are present on both meshes and are used to determine the reflection of a wave at these locations.	103
A.1	Mesh mapping from the physical Cartesian $xy$ -grid to the numerical $\xi\eta$ -grid and vice versa.	108

B.1	Ration between $\tilde{r} =  \tilde{u}_k/u_{giv,k} $ , and $\bar{r} =  \bar{u}_k/u_{giv,k} $ . For different values of $c_\Psi = \Psi/\Delta x^2$ .	125
B.2	Error function for value $\Psi = c_\Psi \Delta x^2 = 0$ .	126
B.3	Several plots of $L^1$ -norm for different locations of the step.	128
B.4	Several plots of the piecewise linear approximation ( $\bar{u}$ ) of the Heaviside function compared to the regularized function ( $\tilde{u}$ ).	129

# List of Symbols

Symbol	Unit	Description
$\Delta t$	s	Time increment
$\Delta x$	m	Space increment, $\Delta x_{i+\frac{1}{2}} = x_{i+1} - x_i$
$\varepsilon_\zeta$	$\text{m s}^{-2}$	Multiplier of the correction term for the essential boundary condition, $\zeta$ -boundary
$\varepsilon_q$	$\text{s}^{-1}$	Multiplier of the correction term for the essential boundary condition, $q$ -boundary
$\mu$	m	Centre of the Gaussian hump
$\nu$	$\text{m}^2 \text{s}^{-1}$	Kinematic viscosity
$\Omega$	—	Finite volume
$\Psi$	$\text{m}^2 \text{s}^{-1}$	Artificial smoothing coefficient
$\sigma$	m	Spreading of the Gaussian hump
$\theta$	—	$\theta$ -method. If $\theta = 1$ then it is a fully implicit method and if $\theta = 0$ then it is a fully explicit method.
$E$	—	Error vector function, defined in computational space
$\xi$	—	Relative coordinate
$\zeta$	m	Water level w.r.t. reference plane, positive upward
$C$	$\text{m}^{\frac{1}{2}} \text{s}^{-1}$	Chézy coefficient
$c_\Psi$	$(.)^{-1}$	Artificial smoothing variable
$c_f$	—	Bed shear stress coefficient
$g$	$\text{m s}^{-2}$	Gravitational constant
$h$	m	Total water depth
$i$	—	node counter
$q$	$\text{m}^2 \text{s}^{-1}$	The water flux in $x$ -direction, $q = hu$
$r$	$\text{m}^2 \text{s}^{-1}$	The water flux in $y$ -direction, $r = hv$
$t$	s	Time coordinate
$t_{reg}$	s	The regularization time for the given time-series
$u$	$\text{m s}^{-1}$	Velocity in $x$ -direction
$v$	$\text{m s}^{-1}$	Velocity in $y$ -direction
$x$	m	$x$ -coordinate
$y$	m	$y$ -coordinate
$z_b$	m	Bed level w.r.t. reference plane, positive upward

# List of To Do's

5.1	The implementation is not stable, check implementation!	48
5.2	Natural boundary: viscosity term	61
F.1	Check next equations	140

# **Introduction**

# 1 Introduction

Nature can be described by mathematical models, these models approximate the behaviour of nature. The main question is: "How well will these mathematical models describe nature?". This document is based on [Borsboom \(1998\)](#), where the mathematical model is called the "*difficult problem*".

To show that the mathematical model does not match with nature by using a numerical method, it is needed that the numerical error of the numerical method can be quantified. The numerical errors should be very small compared to the errors made in the mathematical model. In that case the results of the numerical model is a reliable approximation of the mathematical model. A mismatch in results of the numerical method w.r.t. the nature is then fully determined by the mismatch of the mathematical model.

In this report a derivation is reported of a numerical model that automatically is adjusted to assure that the numerical result is close enough to the solution of the mathematical model. To obtain such a numerical model the mathematical model should be adjusted to a state which is suitable to determine what and how large the mismatch is. The mathematical model is adjusted in that way that the second derivatives of all data is smooth. After smoothing of the data the mathematical model is called "*easy problem*". This step in the procedure is called "*regularization*" and is the first step of the two step FVE method (Finite Volume Element method).

The regularization step has to ensure that the lowest-order terms of the residual of the discretization step are dominant, so that we can limit ourselves to the analysis of the leading terms of the error expansion. The regularization is assumed to be such that the easy problem can be discretized accurately on the available grid, and that the leading terms of the series expansions are dominant.

To obtain this goal the numerical scheme should be central in space, no dissipation is added to the model by the numerical method, just dispersion. All examples in this document will be performed with a fully implicit time-integrator using a iteration mechanism based on the Newton-linearization. The Newton-iteration process benefits of the regularized data. This is the second step of the two step FVE method (Finite Volume Element method).

When all the mentioned items are fulfilled then the numerical scheme is:

- 1 accurate (2nd order, due to the requirement that there is no numerical dissipation),
- 2 reliable (numerical errors are reduced to be much less than the modelling deviations),
- 3 robust (no numerical restrictions on time step other than physical restrictions),
- 4 flexible (separation of numerical and physical part, lot of numerical methods can be used without hampering the physical part),
- 5 efficient (Newton method is a second order method),
- 6 fast (fully implicit).

The feasibility of this method is shown by performing this method on the 1D shallow water equations. Towards these shallow water equations we will look first to the hyperbolic part of these equations. The boundary conditions are separated in a strictly outgoing and a strictly ingoing signal. When selecting a special combination of these signals a weakly-reflective or absorbing boundary condition can be prescribed, including a prescribed ingoing signal.

In [chapter 2: Two-step numerical modeling, error minimizing](#), the error-minimizing integration method is presented. The error-minimizing integration method is based on the assumption that a function can be made smooth so that the numerical discretization and the regularized function are so close that the numerical error is negligible for that function.

In [chapter 4: 1-D Space discretization](#), the one dimensional space discretization. Which consist of a finite volume method and central discretizations and piecewise linear functions between the nodes. Also an estimation of the regularization coefficient for a given function based on the second order of accuracy of the discretization is presented. So the user is able to justify the quality of the numerical solution and in that way to judge where to adjust the regularization or adapt the grid in certain regions.

In [chapter 3: Time integration scheme](#), the fully implicit time integration is based on Newton iteration presented. Due to the regularization of the data the Newton iteration converges extremely well, that is second order in also the more complex areas.

In [chapter 5: Towards the shallow water equations](#), the fully implicit time integration is presented for one dimensional shallow water equations. We start

with the implementation of the 1D advection/transport equation, then with the implementation of the wave equation without convection. This 1D wave equation consist of two independent advection/transport equation for a right and left going signal. At the boundary these two equations are coupled and will therefor generate reflections in the numerical model. We start with 1D advection/transport equation because this equation has the same nature as the right going signal of the wave equation.

In [chapter 6: Numerical experiments](#), several numerical experiments will be shown. Starting with some examples with just a source/sink-term, so only a time integration and without transport and diffusion ([Air pollution](#) and [Brusselator](#)). Followed by numerical experiments of the advection-diffusion equation (with and without diffusion), the 1D-wave equation and 2D-wave equation.

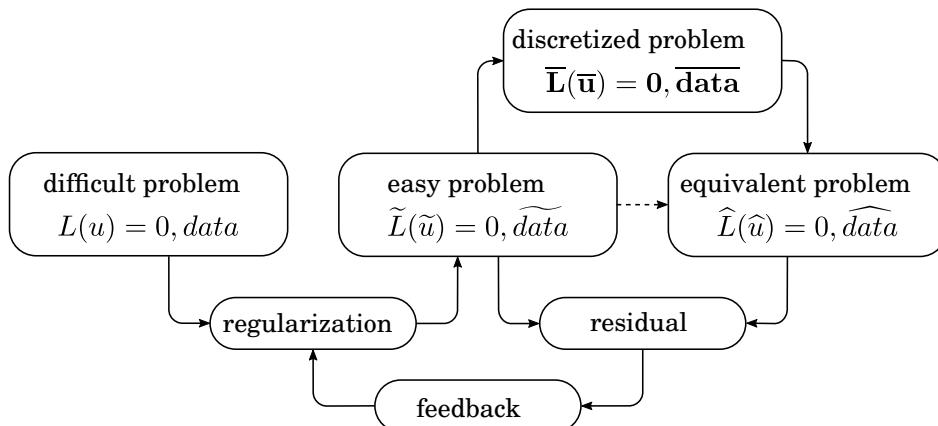
In [section 6.3.1: Outflow boundary layer](#), the fully implicit time integration is presented for the advection-diffusion equation. Showing a flow from left to right with a Dirichlet boundary condition at the outflow side of the domain. The Dirichlet value at the outflow boundary is so chosen that there will appear an outflow boundary layer.

In [section 6.3.2: Interface problem](#), the fully implicit time integration is presented for the advection-diffusion equation. Showing a flow from left to right with a interface in the diffusion coefficient for the transported constituent.

## 2 Two-step numerical modeling, error minimizing

For the realization of our objective, an error analysis is required to gain insight in the relative importance of discretization errors. This has to be in the form of power series expansions to be genuinely generally applicable. Smoothness is required to ensure fast converging series and dominant lowest-order terms that can be used as a basis for reliable local error approximations. Artificial smoothing is added to satisfy this requirement, if necessary. To enable the physical interpretation of numerical errors afterwards, smoothing can only involve the artificial enhancement of physical dissipation. Taylor-series expansions can be used to determine the leading terms of the residual. The residual, however, is not a suitable error measure since it indicates the local discretization error in the equations, not in the solution. In order to be useful, the residual needs to be reformulated in terms of local solution errors. We did not find any existing scheme that allows for such a transformation, and so we developed a discretization method that does. The result turns out to be a method of finite volume type. The discretization consists of integrating the model equations over control volumes, using uniquely defined discrete approximations of all variables. The proposed numerical modeling technique solves the conceptual model problem in two steps (Figure 2.1: in the first step the difficult problem to be solved is changed into an easy problem by adding artificial smoothing; in the second step the easy problem is discretized.

Showing the two-step method in general



**Figure 2.1:** Graphical presentation of the error-minimizing two step method

Notation agreements:

- |             |  |
|-------------|--|
| $u$         | Non-regularized/non-smoothed function, to be determined numerically. |
| $\tilde{u}$ | Regularized/smoothed function, denoted by the wavy line.             |
| $\bar{u}$   | Piecewise linear function, denoted by the bar.                       |
| $\hat{u}$   | Numerical solution on the nodes.                                     |

A tilde ( $\tilde{u}$ ) indicates the variables and differential operators of the easy problem. Their discretizations are indicated by a bar,  $\bar{u}$ . Next, we define the smooth and infinitely differentiable function  $\hat{u}$  that is a very close approximation of numerical solution  $\bar{u}$ . By means of an error analysis we determine the differential problem that  $\hat{u}$  is a solution of. Note that the data pertaining to the computational model are also included in the procedure. Independent variables describing, e.g., the geometry and initial and boundary conditions also need to be discretized and hence need to be sufficiently smooth, to ensure that all higher-order error terms are sufficiently small and can be neglected. Sufficient smoothness is obtained automatically by using smoothing coefficients that are a function of the discretization errors. See also [Borsboom \(2001\)](#).

### 3 Time integration scheme

To derive a time integration method we start from the PDE:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{f}(\mathbf{u}) = 0 \quad (3.1)$$

For conservation types it can be written as:

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot \mathbf{f}(\mathbf{u}) = \mathbf{S} \quad (3.2)$$

and when the finite volume approach is applied, we get

$$\int_{\Omega} \frac{\partial \mathbf{u}}{\partial t} d\Omega + \int_{\Omega} \nabla \cdot \mathbf{f}(\mathbf{u}) d\Omega = \int_{\Omega} \mathbf{S} d\Omega, \quad (3.3)$$

and after Green's theorem

$$\int_{\Omega} \frac{\partial \mathbf{u}}{\partial t} d\Omega + \int_{\Gamma} \mathbf{f}(\mathbf{u}) \cdot \mathbf{n} d\Gamma = \int_{\Omega} \mathbf{S} d\Omega, \quad (3.4)$$

#### 3.1 Fully implicit time integration by adding an iteration process

The system of Equations (3.1) can be written as, including the  $\theta$  method:

$$\Delta t_{inv} \mathbf{M} (\mathbf{u}^{n+1} - \mathbf{u}^n) + \mathbf{f}(\mathbf{u}^{n+\theta}) = 0 \quad (3.5)$$

with  $\Delta t_{inv} = 1/\Delta t$ ,  $\mathbf{M}$  a mass-matrix and  $0 \leq \theta \leq 1$ . The mass-matrix for three adjacent grid nodes as used in this document reads:

$$\mathbf{M} = \begin{pmatrix} \frac{1}{8} & \frac{6}{8} & \frac{1}{8} \end{pmatrix} \quad (3.6)$$

representing a piecewise linear approximation of the function between the grid nodes.

To reach a fully implicit time integration an iteration process  $p$  is added (Borsboom, 2019, eqs. 15/16):

$$\Delta t_{inv} \mathbf{M} (\mathbf{u}^{n+1,p+1} - \mathbf{u}^n) + \mathbf{f}(\mathbf{u}^{n+\theta,p+1}) = 0 \quad (3.7)$$

iterating from  $p \rightarrow p + 1$  until convergence.

The **first** term is split to get a so called "Delta" formulation, taking into account the previous iteration:

$$\Delta t_{inv} \mathbf{M} (\mathbf{u}^{n+1,p+1} - \mathbf{u}^{n+1,p} + \mathbf{u}^{n+1,p} - \mathbf{u}^n) + \mathbf{f}(\mathbf{u}^{n+\theta,p+1}) = 0 \quad (3.8)$$

$$\Delta t_{inv} \mathbf{M} \Delta \mathbf{u}^{n+1,p+1} = - [\Delta t_{inv} \mathbf{M} (\mathbf{u}^{n+1,p} - \mathbf{u}^n) + \mathbf{f}(\mathbf{u}^{n+\theta,p+1})] \quad (3.9)$$

with  $\Delta \mathbf{u}^{n+1,p+1} = \mathbf{u}^{n+1,p+1} - \mathbf{u}^{n+1,p}$ . The right hand side is fully explicit (i.e. known at the previous iteration level  $p$ ). And if the iteration process is converged, the term at the left hand side is zero (i.e.  $\Delta \mathbf{u}^{n+1,p+1} = 0$ ) so the solution of the PDE is reached.

The **second** term of equation (3.5)

$$\dots + \mathbf{f}(\mathbf{u}^{n+\theta,p+1}) = 0 \quad (3.10)$$

will be linearized around the iteration step  $p$  (Newton linearization) and yields

$$\mathbf{f}(\mathbf{u}^{n+\theta,p+1}) = \mathbf{f}(\mathbf{u}^{n+\theta,p}) + \frac{\partial \mathbf{f}(\mathbf{u}^{n+\theta,p})}{\partial \mathbf{u}^{n+1,p}} (\mathbf{u}^{n+\theta,p+1} - \mathbf{u}^{n+\theta,p}) \quad (3.11)$$

$$= \mathbf{f}(\mathbf{u}^{n+\theta,p}) + \frac{\partial \mathbf{f}(\mathbf{u}^{n+\theta,p})}{\partial \mathbf{u}^{n+1,p}} \Delta \mathbf{u}^{n+\theta,p+1} \quad (3.12)$$

with

$$\Delta \mathbf{u}^{n+\theta,p+1} = \mathbf{u}^{n+\theta,p+1} - \mathbf{u}^{n+\theta,p} \quad (3.13)$$

$$= \theta \mathbf{u}^{n+1,p+1} + (1 - \theta) \mathbf{u}^n - \theta \mathbf{u}^{n+1,p} - (1 - \theta) \mathbf{u}^n \quad (3.14)$$

$$= \theta \mathbf{u}^{n+1,p+1} - \theta \mathbf{u}^{n+1,p} \quad (3.15)$$

$$= \theta \Delta \mathbf{u}^{n+1,p+1} \quad (3.16)$$

After substitution of equation (3.16) into equation (3.12) we get:

$$\mathbf{f}(\mathbf{u}^{n+\theta,p+1}) = \mathbf{f}(\mathbf{u}^{n+\theta,p}) + \theta \frac{\partial \mathbf{f}(\mathbf{u}^{n+\theta,p})}{\partial \mathbf{u}^{n+1,p}} \Delta \mathbf{u}^{n+1,p+1}. \quad (3.17)$$

With Jacobian

$$\mathbf{J}^{n+1,p} = \frac{\partial \mathbf{f}(\mathbf{u}^{n+\theta,p})}{\partial \mathbf{u}^{n+1,p}} = \frac{\partial \mathbf{f}(\theta \mathbf{u}^{n+1,p} + (1 - \theta) \mathbf{u}^n)}{\partial \mathbf{u}^{n+1,p}} \quad (3.18)$$

is the approximate linearization of  $f$  as a function of  $\theta \mathbf{u}^{n+1} + (1 - \theta) \mathbf{u}^n$  with respect to  $\mathbf{u}^{n+1,p}$ . The Jacobians needed for the shallow water equations are described in section 3.2.

The whole time integration method read:

$$\begin{aligned} & (\Delta t_{inv} \mathbf{M} + \theta \mathbf{J}^{n+1,p}) \Delta \mathbf{u}^{n+1,p+1} = \\ & = - [\Delta t_{inv} \mathbf{M} (\mathbf{u}^{n+1,p} - \mathbf{u}^n) + \mathbf{f}(\theta \mathbf{u}^{n+1,p} + (1 - \theta) \mathbf{u}^n)] \end{aligned} \quad (3.19)$$

with  $\mathbf{u}^{n+1,p+1} = \mathbf{u}^{n+1,p} + \Delta \mathbf{u}^{n+1,p+1}$  and with an explicit right hand side w.r.t. the iterator  $p$ . In case the Newton iteration process converges, i.e.:

$$\lim_{p \rightarrow \infty} (\Delta \mathbf{u}^{n+1,p+1}) = \lim_{p \rightarrow \infty} (\mathbf{u}^{n+1,p+1} - \mathbf{u}^{n+1,p}) = 0. \quad (3.20)$$

then the left hand side of [equation \(3.19\)](#) is equal to zero and thus it solves the original system of equations:

$$0 = \Delta t_{inv} \mathbf{M} (\mathbf{u}^{n+1,p} - \mathbf{u}^n) + \mathbf{f} (\theta \mathbf{u}^{n+1,p} + (1 - \theta) \mathbf{u}^n). \quad (3.21)$$

Because in the previous part we consider only the first derivative (Jacobian) and assumed that the second derivative is negligible, which is not always true. Therefor we will extend the iteration process, see [section 3.1.1](#). See also: [Borsboom \(1998\)](#) and [Pulliam \(2014\)](#)

### 3.1.1 Pseudo time stepping

In [section 3.1](#) we assumed that only the Jacobian is relevant and the second derivative is negligible. But in some cases it is not the case, so we have to assure that the following inequality is true:

$$\left| \frac{1}{2} \frac{\partial^2 \mathbf{f}(\theta \mathbf{u}^{n+1,p} + (1 - \theta) \mathbf{u}^n)}{(\partial \mathbf{u}^{n+1,p})^2} \Delta \mathbf{u}^{n+1,p+1} \right| < O \left( \left| \frac{\partial \mathbf{f}(\theta \mathbf{u}^{n+1,p} + (1 - \theta) \mathbf{u}^n)}{\partial \mathbf{u}^{n+1,p}} \right| \right) \quad (3.22)$$

Therefor the time integration is extended with a (so called) pseudo timestep method, which reads:

$$\begin{aligned} (\mathbf{M}_{pseu} \mathbf{T}_{pseu}^{n+1,p} + \Delta t_{inv} \mathbf{M} + \theta \mathbf{J}^{n+1,p}) \Delta \mathbf{u}^{n+1,p+1} &= \\ = -(\Delta t_{inv} \mathbf{M} (\mathbf{u}^{n+1,p} - \mathbf{u}^n) + \mathbf{f} (\theta \mathbf{u}^{n+1,p} + (1 - \theta) \mathbf{u}^n)) \end{aligned} \quad (3.23)$$

where  $\mathbf{T}_{pseu}^{n+1,p}$  is a vector containing the inverse of the pseudo timestep, which may vary for all grid nodes, and  $\mathbf{M}_{pseu}$  a mass-matrix operating on the pseudo timestep vector. See for a more detailed description and how to choose the term  $\mathbf{M}_{pseu} \mathbf{T}_{pseu}^{n+1,p}$  [Borsboom \(2019\)](#) and [Buijs \(2024\)](#).

## 3.2 Jacobians

As seen in [section 3.1](#) Jacobians need to be computed. These Jacobians does not contain only derivatives to the major variables but also to place derivatives, which need special attention ([section 3.2.4](#)). For example for the two dimensional convection flux ( $\mathbf{q}\mathbf{q}^T$ ) and pressure term  $gh\nabla\zeta$ , where  $\mathbf{q} = (q, r)^T$  and  $\zeta$  the water level.

As example we take the finite volume approach of the two dimensional non-linear wave equation. This equation reads:

$$\int_{\Omega} \frac{\partial \mathbf{u}}{\partial t} d\Omega + \int_{\Omega} \nabla \cdot \mathbf{F} d\Omega = 0 \Leftrightarrow \int_{\Omega} \frac{\partial \mathbf{u}}{\partial t} d\Omega + \oint_{\Gamma} \mathbf{F} \cdot \mathbf{n} d\Gamma = 0 \quad (3.24)$$

with vector  $\mathbf{u} = (h, q, r)^T$  the Jacobian read. With

$h$	The total water depth, [m]
$q$	The water flux in $x$ -direction, [ $\text{m}^2 \text{s}^{-1}$ ]
$r$	The water flux in $y$ -direction, [ $\text{m}^2 \text{s}^{-1}$ ]

The Jacobian of the function  $F(h, q, r)$  as used in the two dimensional shallow water equations reads:

$$\mathbf{J} = \begin{pmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{pmatrix} = \begin{pmatrix} \frac{\partial F_1}{\partial h} & \frac{\partial F_1}{\partial q} & \frac{\partial F_1}{\partial r} \\ \frac{\partial F_2}{\partial h} & \frac{\partial F_2}{\partial q} & \frac{\partial F_2}{\partial r} \\ \frac{\partial F_3}{\partial h} & \frac{\partial F_3}{\partial q} & \frac{\partial F_3}{\partial r} \end{pmatrix} \quad (3.25)$$

### 3.2.1 Non-linear term, product

If the Jacobian contains non-linear terms, each variable of  $\mathbf{u}$  is linearized before using it in the non-linear term. As an example a product of two quantities is taken, say  $q$  and  $r$  (like the convection term in two dimensional shallow water equations) and  $\Delta q^{n+1,p+1} = \Delta q$  and  $\Delta r^{n+1,p+1} = \Delta r$ :

$$(qr)|^{n+\theta,p+1} = (q^{n+\theta,p} + \theta\Delta q)(r^{n+\theta,p} + \theta\Delta r) \approx \quad (3.26)$$

$$\approx q^{n+\theta,p}r^{n+\theta,p} + q^{n+\theta,p}\theta\Delta r + r^{n+\theta,p}\theta\Delta q \quad (3.27)$$

omitting the quadratic term  $O((\Delta q)^2, \Delta q\Delta r, (\Delta r)^2)$ .

#### Jacobian

When the Jacobian notation is used for the function  $F(q, r) = qr$

$$\mathbf{J} = \begin{pmatrix} J_{11} & J_{12} \end{pmatrix} = \begin{pmatrix} \frac{\partial F}{\partial q} & \frac{\partial F}{\partial r} \end{pmatrix} = \begin{pmatrix} \frac{\partial qr}{\partial q} & \frac{\partial qr}{\partial r} \end{pmatrix} = \begin{pmatrix} r & q \end{pmatrix} \quad (3.28)$$

it leads to following approximation

$$(qr)|^{n+\theta,p+1} \approx q^{n+\theta,p}r^{n+\theta,p} + J_{11}^{n+\theta,p}\theta\Delta q + J_{12}^{n+\theta,p}\theta\Delta r = \quad (3.29)$$

$$= q^{n+\theta,p}r^{n+\theta,p} + r^{n+\theta,p}\theta\Delta q + q^{n+\theta,p}\theta\Delta r \quad (3.30)$$

### 3.2.2 Non-linear term, quotient

If the Jacobian contains non-linear terms, each variable of  $\mathbf{u}$  is linearized before using it in the non-linear term. In this example a quotient of two quantities is taken, say  $q$  and  $h$  (representing the velocity in the two dimensional shallow water equations) and  $\Delta q^{n+1,p+1} = \Delta q$  and  $\Delta h^{n+1,p+1} = \Delta h$ :

$$\left(\frac{q}{h}\right)^{n+\theta,p+1} = \frac{q^{n+\theta,p} + \theta\Delta q}{h^{n+\theta,p} + \theta\Delta h} \approx \quad (3.31)$$

$$\approx \frac{q^{n+\theta,p} + \theta\Delta q}{h^{n+\theta,p}} \left(1 - \frac{\theta}{h^{n+\theta,p}}\Delta h + O((\Delta h)^2)\right) \approx \quad (3.32)$$

$$\approx \left(\frac{q^{n+\theta,p}}{h^{n+\theta,p}} + \frac{1}{h^{n+\theta,p}}\theta\Delta q\right) \left(1 - \frac{1}{h^{n+\theta,p}}\theta\Delta h + O((\Delta h)^2)\right) \approx \quad (3.33)$$

$$\approx \frac{q^{n+\theta,p}}{h^{n+\theta,p}} - \frac{q^{n+\theta,p}}{(h^{n+\theta,p})^2}\theta\Delta h + \frac{1}{h^{n+\theta,p}}\theta\Delta q \quad (3.34)$$

omitting the quadratic term  $O((\Delta q)^2, \Delta q\Delta h, (\Delta h)^2)$ .

#### Jacobian

When the Jacobian notation is used for the function  $F(h, q) = q/h$

$$\mathbf{J} = \begin{pmatrix} J_{11} & J_{12} \end{pmatrix} = \begin{pmatrix} \frac{\partial F}{\partial h} & \frac{\partial F}{\partial q} \end{pmatrix} = \begin{pmatrix} \frac{\partial q/h}{\partial h} & \frac{\partial q/h}{\partial q} \end{pmatrix} = \begin{pmatrix} -\frac{q}{h^2} & \frac{1}{h} \end{pmatrix} \quad (3.35)$$

it leads to following approximation

$$\left(\frac{q}{h}\right)^{n+\theta,p+1} \approx \frac{q^{n+\theta,p}}{h^{n+\theta,p}} + J_{11}^{n+\theta,p}\theta\Delta h + J_{12}^{n+\theta,p}\theta\Delta q = \quad (3.36)$$

$$= \frac{q^{n+\theta,p}}{h^{n+\theta,p}} - \frac{q^{n+\theta,p}}{(h^{n+\theta,p})^2}\theta\Delta h + \frac{1}{h^{n+\theta,p}}\theta\Delta q \quad (3.37)$$

### 3.2.3 Non-linear term, product and quotient

For this example we look to the Jacobian as they appear for the convection term in two dimensions:

$$\left(\frac{qr}{h}\right)^{n+\theta,p+1} = \frac{(q^{n+\theta,p} + \theta\Delta q)(r^{n+\theta,p} + \theta\Delta r)}{h^{n+\theta,p} + \theta\Delta h}. \quad (3.38)$$

#### Jacobian

When the Jacobian notation is used for the function  $F(h, q, r) = qr/h$

$$\mathbf{J} = \begin{pmatrix} J_{11} & J_{12} & J_{13} \end{pmatrix} = \begin{pmatrix} \frac{\partial F}{\partial h} & \frac{\partial F}{\partial q} & \frac{\partial F}{\partial r} \end{pmatrix} = \quad (3.39)$$

$$= \begin{pmatrix} \frac{\partial qr/h}{\partial h} & \frac{\partial qr/h}{\partial q} & \frac{\partial qr/h}{\partial r} \end{pmatrix} = \begin{pmatrix} -\frac{qr}{h^2} & \frac{r}{h} & \frac{q}{h} \end{pmatrix} \quad (3.40)$$

it leads to following approximation

$$\left(\frac{qr}{h}\right)^{n+\theta,p+1} \approx \frac{q^{n+\theta,p}r^{n+\theta,p}}{h^{n+\theta,p}} + J_{11}^{n+\theta,p}\theta\Delta h + J_{12}^{n+\theta,p}\theta\Delta q + J_{13}^{n+\theta,p}\theta\Delta r = \\ (3.41)$$

$$= \frac{q^{n+\theta,p}r^{n+\theta,p}}{h^{n+\theta,p}} - \frac{q^{n+\theta,p}r^{n+\theta,p}}{(h^{n+\theta,p})^2}\theta\Delta h + \frac{r^{n+\theta,p}}{h^{n+\theta,p}}\theta\Delta q + \frac{q^{n+\theta,p}}{h^{n+\theta,p}}\theta\Delta r \\ (3.42)$$

in case  $q$  is substitute for  $r$  then  $\partial/\partial r = 0$  and the approximation reads:

$$\left(\frac{qq}{h}\right)^{n+\theta,p+1} \approx \frac{q^{n+\theta,p}q^{n+\theta,p}}{h^{n+\theta,p}} - \frac{q^{n+\theta,p}q^{n+\theta,p}}{(h^{n+\theta,p})^2}\theta\Delta h + \frac{2q^{n+\theta,p}}{h^{n+\theta,p}}\theta\Delta q. \\ (3.43)$$

### 3.2.4 Terms with an operator

The Jacobian of an operator is also applied to the argument of the operator. As an example the pressure term of the shallow water equations is taken, where  $\Delta h^{n+1,p+1} = \Delta h$  and  $\Delta \zeta^{n+1,p+1} = \Delta \zeta$ :

$$gh\frac{\partial \zeta}{\partial x}^{n+\theta,p+1} \approx g(h^{n+\theta,p} + \theta\Delta h)\frac{\partial}{\partial x}(\zeta^{n+\theta,p} + \theta\Delta \zeta) \approx \\ (3.44)$$

$$\approx gh^{n+\theta,p}\frac{\partial \zeta^{n+\theta,p}}{\partial x} + gh^{n+\theta,p}\frac{\partial}{\partial x}(\theta\Delta \zeta) + g\frac{\partial \zeta^{n+\theta,p}}{\partial x}\theta\Delta h \\ (3.45)$$

omitting the quadratic term  $O(\Delta h \partial \Delta \zeta / \partial x)$ . The term  $\partial \Delta \zeta / \partial x$  is not always small and therefor a psuedo time step method is introduced, see [section 3.1.1](#).

In discrete form it reads on location  $x_{i+\frac{1}{2}}$ :

$$gh\frac{\partial \zeta}{\partial x}^{n+\theta,p+1} \approx gh_{i+\frac{1}{2}}^{n+\theta,p}\frac{\zeta_{i+1}^{n+\theta,p} - \zeta_i^{n+\theta,p}}{\Delta x_i} + gh_{i+\frac{1}{2}}^{n+\theta,p}\frac{\theta\Delta \zeta_{i+1} - \theta\Delta \zeta_i}{\Delta x_i} + \\ (3.46)$$

$$+ g\frac{\zeta_{i+1}^{n+\theta,p} - \zeta_i^{n+\theta,p}}{\Delta x_i}\theta\Delta h_{i+\frac{1}{2}} \\ (3.47)$$

Remember that the gradient over a grid cell  $\Delta x_i$  is constant, due to the piecewise linear approximation between two nodes.

#### Jacobian

When the Jacobian notation is used for the function  $F(q, h) = gh \partial \zeta / \partial x$

$$\mathbf{J} = \begin{pmatrix} J_{11} & J_{12} \end{pmatrix} = \begin{pmatrix} \frac{\partial F}{\partial h} & \frac{\partial F}{\partial \zeta} \end{pmatrix} = \begin{pmatrix} \frac{\partial(gh \partial \zeta / \partial x)}{\partial h} & \frac{\partial(gh \partial \zeta / \partial x)}{\partial \zeta} \end{pmatrix} = \begin{pmatrix} g \frac{\partial \zeta}{\partial x} & gh \frac{\partial}{\partial x} \end{pmatrix} \\ (3.48)$$

it leads to following approximation

$$gh \frac{\partial \zeta}{\partial x} \Big|_{i+\frac{1}{2}}^{n+\theta,p+1} \approx gh^{n+\theta,p} \frac{\partial \zeta^{n+\theta,p}}{\partial x} + J_{11}\theta \Delta h + J_{12} \frac{\partial}{\partial x}(\theta \Delta \zeta) \approx \quad (3.49)$$

$$\approx gh^{n+\theta,p} \frac{\zeta^{n+\theta,p}_{i+1} - \zeta^{n+\theta,p}_i}{\Delta x_i} + g \frac{\zeta^{n+\theta,p}_{i+1} - \zeta^{n+\theta,p}_i}{\Delta x_i} \theta \Delta h_{i+\frac{1}{2}} + \quad (3.50)$$

$$+ gh_{n+\frac{1}{2}}^{n+\theta,p} \frac{\theta \Delta \zeta_{i+1} - \theta \Delta \zeta_i}{\Delta x_i} \quad (3.51)$$

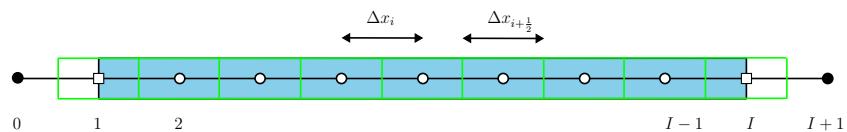
# 4 1-D Space discretization

We are looking for a second order central space discretization together with the finite volume approach. So the higher order terms in the Taylor series expansion are negligible. For this numerical discretization method no dissipation is added, only there is some dispersion for the shorter waves, i.e. dependent on the third derivative in the Taylor expansion. To fulfill this requirement the data should be smooth according to the truncation error of the numerical discretization. If not, the data should be made smooth with a procedure in which you can see on which location the smoothing is severe. The process of smoothing is called regularization. If the truncation error (high values of second derivatives) is severe on locations that the user do not expect and do not accept then the user can adjust the discretization in that part of the domain. There are two options to adjust the data:

- 1 increase the smoothing coefficient or
- 2 choose a smaller grid size.

## 4.1 Finite volume approach

We will discuss the finite volume approach for the one dimensional case of the function  $u(x, t)$ , for the grid shown in [Figure 4.1](#)



**Figure 4.1:** Water body (blue area), finite volumes (green boxes), computational points (open dots), virtual computational points (black dots), boundary points (open squares) are at  $i = 1$  (west boundary) and  $i = I$  (east boundary).

The control volume is defined on the interval  $x_{i-\frac{1}{2}}$  to  $x_{i+\frac{1}{2}}$ , see [Figure 4.1](#). The grid in [Figure 4.1](#) is equidistant but that is not necessarily, the method which is described in this document also holds for a non-equidistant grid.

### 4.1.1 Quadrature rule, source term

In this section the 1-point Gauss and 2-point Gauss integration methods are shown for a 1D linear function and for a 1D quadratic function.

#### 4.1.1.1 1-point Gauss

The finite volume approach for the function  $u(x, t)$  reads:

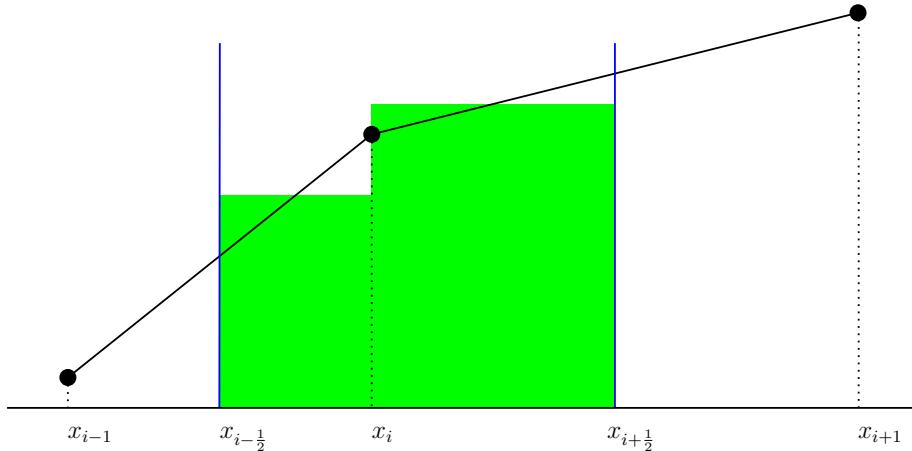
$$\int_{\Omega} u d\omega = \int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} u dx \quad (4.1)$$

Using piecewise linear functions between the non-equidistant nodes the quadrature rule reads:

$$\int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} u dx = \int_{x_{i-\frac{1}{2}}}^{x_i} u dx + \int_{x_i}^{x_{i+\frac{1}{2}}} u dx \approx \quad (4.2)$$

$$\approx \frac{\Delta x_{i-\frac{1}{2}}}{2} \frac{u_{i-1} + 3u_i}{4} + \frac{\Delta x_{i+\frac{1}{2}}}{2} \frac{3u_i + u_{i+1}}{4} \quad (4.3)$$

where the control volume is split into two adjacent sub-control volumes  $[x_{i-\frac{1}{2}}, x_i]$  and  $[x_i, x_{i+\frac{1}{2}}]$ . A graphical interpretation of this method is given in [Figure 4.2](#).

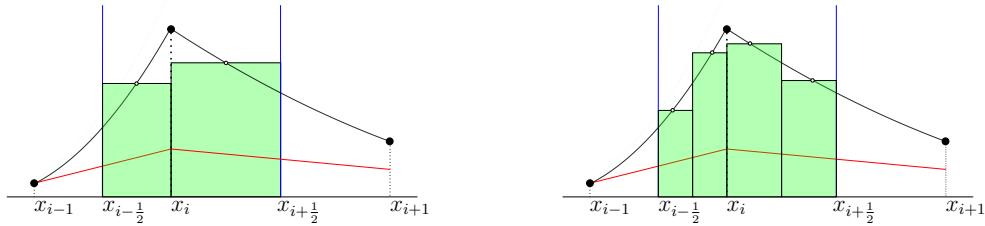


**Figure 4.2:** 1-point Gauss integration of a linear function around  $x_i$  over the control volume from  $x_{i-\frac{1}{2}}$  to  $x_{i+\frac{1}{2}}$ , which is exact. Black line: linear function between dots. Open bullets the integration points.

Higher order quadrature rules may be chosen, but they are not discussed in this report, but an illustration is given in [section 4.1.1.2](#).

#### 4.1.1.2 2-point Gauss

In this section the difference is graphical shown between integration over a finite volume by 1-point Gauss and a 2-point Gauss integration.



(a) Quadratic function approximated by 1-point Gauss.

(b) Quadratic function approximated by 2-point Gauss.

**Figure 4.3:** Integration of a quadratic function over the control volume  $[x_{i-\frac{1}{2}}, x_{i+\frac{1}{2}}]$ . 1-point Gauss is exact **only** for constant and linear functions, 2-points Gauss is exact for constant, linear, quadratic and cubic functions.

#### 4.1.2 Boundary conditions

At the west and east boundary boundary conditions need to be supplied. If it is a prescribed boundary condition (ingoing signal) it is called an **essential**-boundary condition, if the boundary condition is determined by the outgoing signal it is called a **natural**-boundary condition (Logan, 1987; Kan et al., 2008). In case of a wave equation we have a right and left going signal. When no reflection at an open boundary is required then at the west boundary a signal need to be prescribed without disturbing the left going signal. And at the east boundary the other way around.

Further more we prescribe the boundary signal at the boundary node of the grid. This assumption is made because the user is acquainted with the fact that open boundaries are given at nodes. But for the outgoing signal this is not necessarily, for the outgoing signal we stick to the finite volume approach.

When we consider a one dimensional right going signal (see section 5.2.1) the boundary at the west side is located at  $x_1$  (essential) and the outflow condition is located at  $x_{I+\frac{1}{2}}$  (natural). The prescribed function reads:

$$c(0, t) = f(t) \quad (4.4)$$

Because we use a 3-point stencil for the interior, we aim for a 3-point stencil for the essential boundary condition. One possible quadratic interpolation is a parabolic fit through the grid points, giving an under specification of the solu-

tion at the boundary regardless of its position.

$$\begin{aligned} c_{GP}(\xi) &= c_0(1 - \xi) + c_1\xi + \frac{1}{2}(c_0 - 2c_1 + c_2)(\xi - 1)\xi = \\ &= (1 - \xi) \left(1 - \frac{1}{2}\xi\right)c_0 + \xi(2 - \xi)c_1 + \frac{1}{2}\xi(\xi - 1)c_2 \end{aligned} \quad (4.5)$$

where  $\xi \in [0, 1]$  is the weight function between  $c_0$  and  $c_1$ .

Another possible quadratic fit is the one through Cell-Centered values:

$$\begin{aligned} c_{CC}(\xi) &= c_0(1 - \xi) + c_1\xi + \frac{1}{2}(c_0 - 2c_1 + c_2) \left(\xi - \frac{1}{2}\right)^2 \\ &= \left(1 - \xi + \frac{1}{2}\left(\xi - \frac{1}{2}\right)^2\right)c_0 + \left(\xi - \left(\xi - \frac{1}{2}\right)^2\right)c_1 + \left(\frac{1}{2}\left(\xi - \frac{1}{2}\right)^2\right)c_2 \end{aligned} \quad (4.6)$$

(4.7)

The parabolic fit that gives neither underspecification nor overspecification of imposed values at boundaries is a combination of [equation \(4.5\)](#) and [\(4.7\)](#). It is easy to show that the optimal combination consists of 1/3 times [equation \(4.5\)](#) plus 2/3 times [equation \(4.7\)](#), which yields:

$$c_{opt}(\xi) = \left(\frac{13}{12} - \frac{3}{2}\xi - \frac{1}{2}\xi^2\right)c_0 + \left(-\frac{1}{6} + 2\xi - \xi^2\right)c_1 + \left(\frac{1}{12} - \frac{1}{2}\xi + \frac{1}{2}\xi^2\right)c_2 \quad (4.8)$$

Which give the following interpolation values for  $\xi = \frac{1}{2}$  and  $\xi = 1$ :

$$c_{opt}\left(\frac{1}{2}\right) = \frac{11}{24}c_0 + \frac{14}{24}c_1 - \frac{1}{24}c_2 \quad (4.9)$$

$$c_{opt}(1) = \frac{1}{12}c_0 + \frac{10}{12}c_1 + \frac{1}{12}c_2 \quad (4.10)$$

Where [equation \(4.9\)](#) will be used for the essential boundary condition as it is located at the boundary of a finite volume and [equation \(4.10\)](#) will be used for the essential boundary condition as it is located on a node.

Verification of its correctness by means of integration over the outermost finite volume yields:

$$\int_{\frac{1}{2}}^{\frac{3}{2}} c_{opt}(\xi) d\xi = \frac{1}{8}c_0 + \frac{3}{4}c_1 + \frac{1}{8}c_2 \quad (4.11)$$

In the right-hand side we see the weights of the mass matrix of the piecewise linear FVE method, i.e. averaged over the left outermost finite volume the quadratic function  $c_{opt}$  equals the piecewise linear function used in the FVE scheme.

## 4.2 Regularization of artificial viscosity $\Psi$

To get an error-minimizing method we need to regularize all data, as mentioned in [chapter 2](#). Regularization of the artificial viscosity  $\Psi$  is performed as described in [Borsboom \(2001, eq. 14\)](#).

$$\int_{\Omega} \Psi d\omega - \alpha_{\psi} \int_{\Omega} \Delta \xi^2 \frac{\partial^2 \Psi}{\partial \xi^2} d\omega = \int_{\Omega} \beta_{\psi} Err_{\beta_{\psi}} d\omega \quad (4.12)$$

When discretized it yields ([Borsboom, 2001](#), eq. 18):

$$\left( \frac{1}{8} - \alpha_{\psi} \right) \Psi_{i-1} + \left( \frac{3}{4} + 2\alpha_{\psi} \right) \Psi_i + \left( \frac{1}{8} - \alpha_{\psi} \right) \Psi_{i+1} = \frac{\beta_{\psi}}{\Delta \xi} \int_{\xi_{i-\frac{1}{2}}}^{\xi_{i+\frac{1}{2}}} Err_{\beta_{\psi}} d\xi \quad (4.13)$$

The right hand side of [equation \(4.13\)](#) can be approximated by:

$$\frac{\beta_{\psi}}{\Delta \xi} \int_{\xi_{i-\frac{1}{2}}}^{\xi_{i+\frac{1}{2}}} Err_{\beta_{\psi}} d\xi = \frac{\beta_{\psi}}{\Delta \xi} \int_{\xi_{i-\frac{1}{2}}}^{\xi_i} Err_{\beta_{\psi}} d\xi + \frac{\beta_{\psi}}{\Delta \xi} \int_{\xi_i}^{\xi_{i+\frac{1}{2}}} Err_{\beta_{\psi}} d\xi \approx \quad (4.14)$$

$$\approx \frac{\beta_{\psi}}{\Delta \xi} \frac{1}{2\Delta \xi} (Err_{\beta_{\psi}})_{i-\frac{1}{4}} + \frac{\beta_{\psi}}{\Delta \xi} \frac{1}{2\Delta \xi} (Err_{\beta_{\psi}})_{i+\frac{1}{4}} \quad (4.15)$$

For  $Err_{\beta_{\psi}}$  the following expression is used (comparable to [Borsboom \(2001, eq. 42\)](#), a derivation of this expression is given in [Appendix D](#)):

$$Err_{\beta_{\psi}} = \Delta \xi \bar{x}_{\xi} \left( \frac{1}{16} \sqrt{\frac{g}{\bar{h}}} |D_{\xi}(\bar{\zeta})| + \frac{1}{16} \sqrt{2} \left| \frac{D_{\xi}(\bar{q})}{\bar{h}} - \frac{\bar{q} D_{\xi}(\bar{h})}{\bar{h}^2} \right| \right) \quad (4.16)$$

For the Weir experiment ([section 6.4.2](#)) the following parameters are used,  $\alpha_{\psi} = c_{\Psi}$  and  $\beta_{\psi} = 32c_{\Psi}$  which are educational guesses!.

Using (with  $\bar{u} \in \{\bar{h}, \bar{q}\}$ ):

$$\bar{u}_{i-\frac{1}{4}} = \frac{1}{4}(u_{i-1} + 3u_i), \quad \bar{u}_{i+\frac{1}{4}} = \frac{1}{4}(u_{i+1} + 3u_i) \quad (4.17)$$

and

$$(\bar{x}_{\xi})_{i-\frac{1}{4}} = x_i - x_{i-1}, \quad (\bar{x}_{\xi})_{i+\frac{1}{4}} = x_{i+1} - x_i \quad (4.18)$$

and for equidistant meshes we use ([Borsboom, 2001, eq. 35](#)):

$$D_{\xi}(\bar{u}) = \Delta \xi^2 \frac{\partial^2}{\partial \xi^2} \approx u_{i-1} - 2u_i + u_{i+1}. \quad (4.19)$$

## 4.3 Regularization of given function

To get an error-minimizing method we need to regularize all data, as mentioned in chapter 2. Regularization of a given function is performed as described in Borsboom (1998) and Borsboom (2003). The given function to regularize reads:

$$u_{giv}(x). \quad (4.20)$$

Some notation agreements are:

- $u$  Non-regularized/non-smoothed function, to be determined numerically.
- $\tilde{u}$  Regularized/smoothed function, denoted by the wavy line.
- $\bar{u}$  Piecewise linear function, denoted by the bar.
- $u_i$  Value of the numerical value at point  $x_i$ , denoted by the subscript.

The regularized function  $\tilde{u}$  satisfy the next equation (Borsboom, 1998, eq. 6):

$$\tilde{u} - \frac{\partial}{\partial x} \Psi \frac{\partial \tilde{u}}{\partial x} = u_{giv}, \quad \Psi = c_\Psi \Delta x^2 E, \quad (4.21)$$

where

- $u_{giv}$  Given function, ex. bathymetry, viscosity,  $\dots$ ,  $[\cdot]$ .
- $\tilde{u}$  Regularized/smoothed function of  $u_{giv}$ ,  $[\cdot]$ .
- $\Psi$  (Artificial) smoothing coefficient,  $[m^2]$
- $\Delta x$  Space discretization,  $\Delta x_{i+\frac{1}{2}} = x_{i+1} - x_i$ ,  $[m]$
- $c_\Psi$  Smoothing factor (set by user),  $[1/\cdot]$
- $E$  Error function,  $[\cdot]$  (see section 4.3.1)

First the discretization of equation (F.1) is discussed and second the determination of the artificial smoothing coefficient  $\Psi$ .

The finite volume approach of equation (F.1) reads:

$$\int_{\Omega} \tilde{u} d\Omega - \int_{\Omega} \frac{\partial}{\partial x} \Psi \frac{\partial \tilde{u}}{\partial x} d\Omega = \int_{\Omega} u_{giv} d\Omega \quad (4.22)$$

### Integration of the first term

Integration of the first term yields:

$$\int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \tilde{u} dx \approx \frac{1}{2} \Delta x_{i-\frac{1}{2}} \left( \frac{1}{4} u_{i-1} + \frac{3}{4} u_i \right) + \frac{1}{2} \Delta x_{i+\frac{1}{2}} \left( \frac{3}{4} u_i + \frac{1}{4} u_{i+1} \right) \quad (4.23)$$

### Integration of the second term

Integration of the second term, with  $\Psi_{i+\frac{1}{2}} = \frac{1}{2}(\Psi_i + \Psi_{i+1})$ :

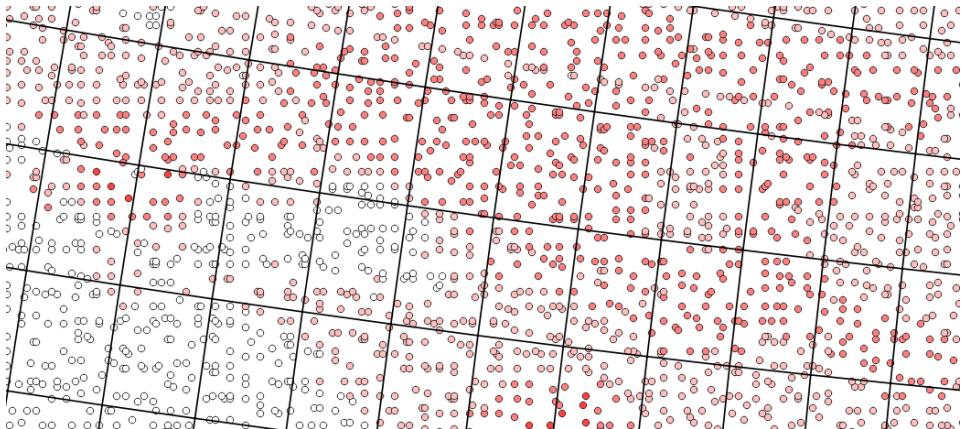
$$\int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \frac{\partial}{\partial x} \Psi \frac{\partial \tilde{u}}{\partial x} dx = \Psi \frac{\partial \tilde{u}}{\partial x} \Big|_{i+\frac{1}{2}} - \Psi \frac{\partial \tilde{u}}{\partial x} \Big|_{i-\frac{1}{2}} \approx \quad (4.24)$$

$$\approx \Psi_{i+\frac{1}{2}} \frac{u_{i+1} - u_i}{\Delta x_{i+\frac{1}{2}}} - \Psi_{i-\frac{1}{2}} \frac{u_i - u_{i-1}}{\Delta x_{i-\frac{1}{2}}} = \quad (4.25)$$

$$= \frac{\Psi_{i-\frac{1}{2}}}{\Delta x_{i-\frac{1}{2}}} u_{i-1} - \left( \frac{\Psi_{i-\frac{1}{2}}}{\Delta x_{i-\frac{1}{2}}} + \frac{\Psi_{i+\frac{1}{2}}}{\Delta x_{i+\frac{1}{2}}} \right) u_i + \frac{\Psi_{i+\frac{1}{2}}}{\Delta x_{i+\frac{1}{2}}} u_{i+1} \quad (4.26)$$

### Integration of the right hand side

For the integration of the right hand side we could use a smaller integration step size, to incorporate the sub-grid scale effects. If the function  $u_{giv}$  is for example an analytic function this integral can be computed exact or data is given by a lot of measurement points per finite volume, see for example [Figure 4.4](#). When integrating over a finite volume the sub-grid scale effects will be taken into account



**Figure 4.4:** Two dimensional example of a lot of data points per grid cell. The data points are used to compute the integral at the right hand side of [equation \(4.28\)](#).

### Discretization of equation (4.22)

So the discretization of [equation \(4.22\)](#) with  $\alpha = \frac{1}{8}$ , read (i.e. [Borsboom \(1998, eq. 7\)](#) and [Borsboom \(2003, eq. 6\)](#)):

$$\left( \frac{\Delta x_{i-\frac{1}{2}}}{8} - \frac{\Psi_{i-\frac{1}{2}}}{\Delta x_{i-\frac{1}{2}}} \right) u_{i-1} + \left( \frac{3\Delta x_{i-\frac{1}{2}}}{8} + \frac{\Psi_{i-\frac{1}{2}}}{\Delta x_{i-\frac{1}{2}}} + \frac{3\Delta x_{i+\frac{1}{2}}}{8} + \frac{\Psi_{i+\frac{1}{2}}}{\Delta x_{i+\frac{1}{2}}} \right) u_i + \quad (4.27)$$

$$+ \left( \frac{\Delta x_{i+\frac{1}{2}}}{8} - \frac{\Psi_{i+\frac{1}{2}}}{\Delta x_{i+\frac{1}{2}}} \right) u_{i+1} = \int_{x_{i-1/2}}^{x_{i+\frac{1}{2}}} u_{giv} dx \quad (4.28)$$

The boundary conditions to close the three diagonal system are  $u_0 = u_{giv}(x_0)$  and  $u_{I+1} = u_{giv}(x_{I+1})$ .

### 4.3.1 Determination of artificial smoothing coefficient $\Psi$

The artificial smoothing coefficient  $\Psi$  ( $= c_\psi \Delta x^2 E$ , [equation \(F.1\)](#)) is dependent on error  $E$ , the smoothing coefficient  $c_E$  and the second derivative of the given function  $u_{giv}$  ([Borsboom, 1998](#), eq. 8). The error  $E$  will be computed in computational space, meaning that a disturbance is spreaded over an equal number of cells before and after the location of the disturbance:

$$\left( \frac{\Delta\xi}{8} - \frac{c_E}{\Delta\xi} \right) E_{i-1} + \left( \frac{6\Delta\xi}{8} + \frac{2c_E}{\Delta\xi} \right) E_i + \left( \frac{\Delta\xi}{8} - \frac{c_E}{\Delta\xi} \right) E_{i+1} = \int_{\xi_{i-\frac{1}{2}}}^{\xi_{i+\frac{1}{2}}} |D_i| d\xi \quad (4.29)$$

with  $\Delta\xi = 1$  it reads:

$$\left( \frac{1}{8} - c_E \right) E_{i-1} + \left( \frac{6}{8} + 2c_E \right) E_i + \left( \frac{1}{8} - c_E \right) E_{i+1} = |D_i| \quad (4.30)$$

**Choose  $c_E$  equal to  $c_\psi$**  and take into account that  $D_i$  is constant over a control volume

$$D_i = \Delta\xi^2 \frac{\partial^2 u_{giv}}{\partial\xi^2} \quad (\text{Borsboom, 1998, eq. 2}) \quad (4.31)$$

$$\approx u_{giv_{i-1}} - 2u_{giv_i} + u_{giv_{i+1}} \quad (4.32)$$

Now system the system of [equation \(F.27\)](#) can be solved and where  $\Psi$  is set to:

$$\Psi = c_\Psi \Delta x^2 E \quad (4.33)$$

For an estimation of  $c_\Psi$  see [section B.2](#), in this document we use  $c_\Psi = 4$ .

The boundary conditions to close the three diagonal system are:

$$2E_0 - E_1 = |D_1| \quad \text{and} \quad (4.34)$$

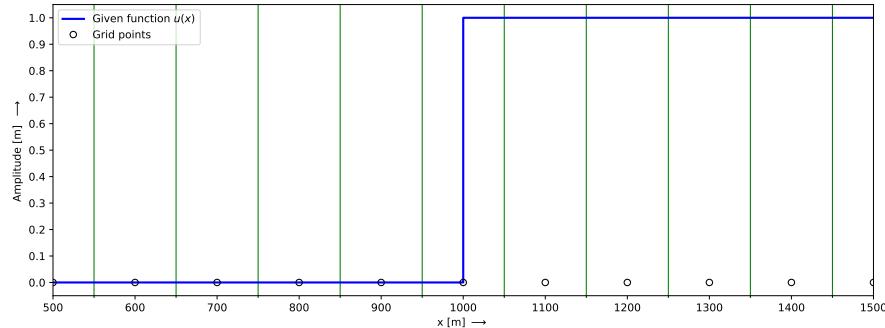
$$-E_I + 2E_{I+1} = |D_I|. \quad (4.35)$$

### 4.3.2 Step function (Heaviside function)

For a full description of this example see [Borsboom \(2003](#), eq. 5). The function is initially defined as:

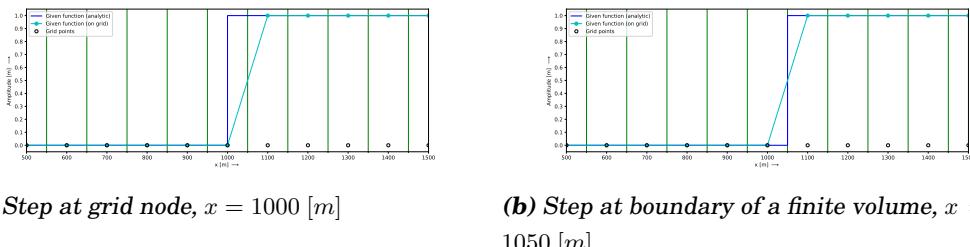
$$u_{given}(x) = \begin{cases} 0, & \text{if } 0 [m] \leq x \leq 1000 [m], \\ 1, & \text{if } 1000 [m] < x \leq 2000 [m], \end{cases} \quad (4.36)$$

For illustration, the step is chosen to be exactly on a grid point (in the middle of a control volume at 1000 [m]) and at the finite volume boundary, i.e. a half  $\Delta x$  shifted to the right.



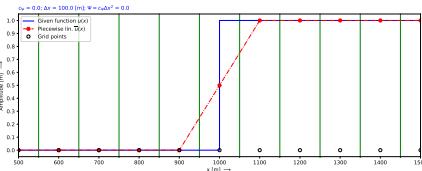
**Figure 4.5:** Step function to be estimated. The thin green vertical lines indicate the borders of the finite volumes.

A straight forward piecewise approximation is shown in Figure 4.6. Both figures does show the same discretization function (cyan colored) but the step is at a different location.

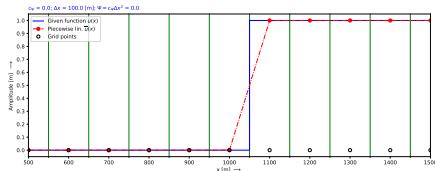


**Figure 4.6:** As seen from this figures the function defined on the grid nodes does not see the exact location of the step. Both functions through the grid nodes have the same profile, but the step is at another location.

A piecewise approximation with a regularization coefficient of zero ( $c_\Psi = 0$ ) is shown in Figure 4.7.



(a) Step at grid node,  $x = 500$  [m]



(b) Step at boundary finite volume,  $x = 550$  [m]

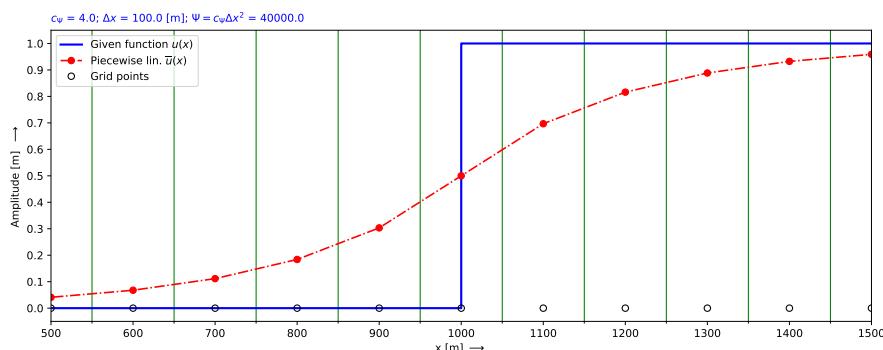
**Figure 4.7:** Step function approximated by a piecewise linear function (red line with dots at the nodes),  $c_\Psi = 0$ ,  $\Delta x = 100$  [m] and  $\Psi = 0$ . The thin green vertical lines indicate the borders of the finite volumes.

As seen from Figure 4.7 the step is more taken into account as is presented in Figure 4.6. Which looks quite well, but what are the values of the second derivative of the solution. For  $\Delta x = 100$  [m] the absolute value of the second derivative is  $0.5/(100)^2$  (Figure 4.7a) and  $1.0/(100)^2$  (Figure 4.7b).

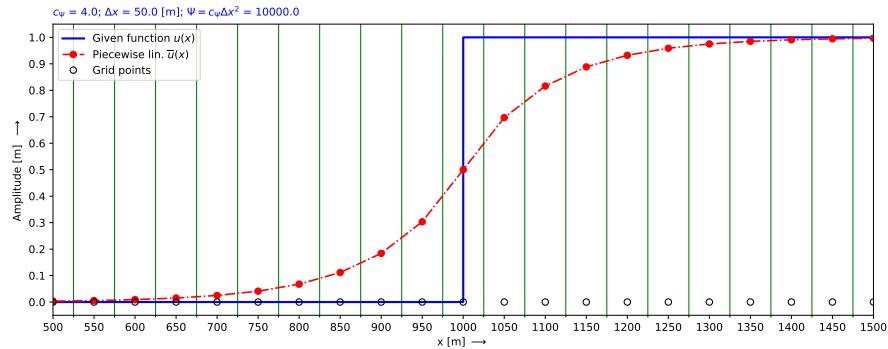
There are two options to estimate this step function by a piecewise linear smooth function with the same numerical accuracy:

- 1 Regularization with using a large grid size, the numerical solution is less close to the step function (see Figure 4.8)
- 2 Regularization with using a small grid size, the numerical solution is closer to the step function (see Figure 4.9),

Both options has the same value for  $c_\Psi = 4$ . Meaning that the step is represented by the same number of grid cells. How to estimate  $c_\Psi$  can be read in Appendix B. It is up to the user which regularization is can be used for the numerical simulation. A better representation of the step function need a smaller grid size.



**Figure 4.8:** Step function approximated by a piecewise linear function (red line with dots at the nodes),  $c_\Psi = 4$ ,  $\Delta x = 100$  [m] and  $\Psi = 40000$ . The thin green vertical lines indicate the borders of the finite volumes.



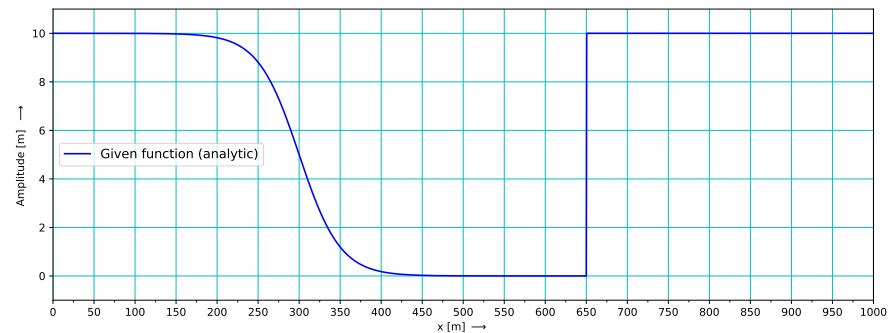
**Figure 4.9:** Step function approximated by a piecewise linear function (red line with dots at the nodes),  $c_\Psi = 4$ ,  $\Delta x = 50$  [m] and  $\Psi = 10000$ . The thin green vertical lines indicate the borders of the finite volumes.

### 4.3.3 Small and a large gradient in the data set

To show the influence of regularization a more general data set is chosen, Borsboom (1998) (given function, here adjusted). A given function with a small (smooth) and large (steep) gradients in the data set is chosen. The function is defined by:

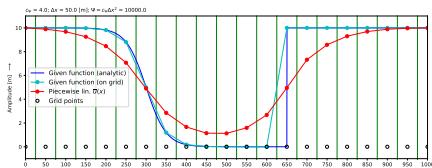
$$u_{\text{given}}(x) = \begin{cases} 10 \left( \frac{1}{2} - \frac{1}{2} \tanh(20x/1000 - 6) \right), & \text{if } 0 \text{ [m]} \leq x \leq 650 \text{ [m]}, \\ 10, & \text{if } 650 \text{ [m]} < x \geq 1000 \text{ [m]}, \end{cases} \quad (4.37)$$

and shown in Figure 4.10:

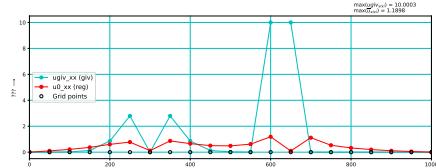


**Figure 4.10:** Large and small gradients in given function.

First guess of regularization:



(a) Grid size  $\Delta x = 50$  [m]



(b) Second derivatives, normalized grid size  
 $\Delta \xi = 1$ .

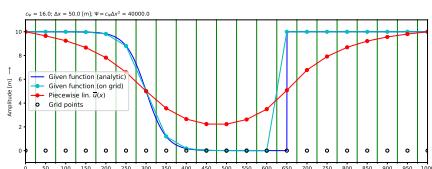
**Figure 4.11:** Initial guess ( $c_\Psi = 4, \Delta x = 50$  [m])

There are two options to adjust the data:

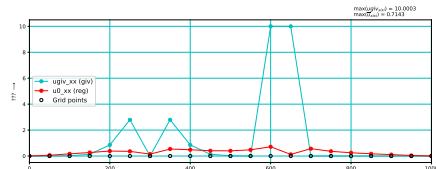
- 1 increase the regularization coefficient or
- 2 choose a smaller grid size.

### Regularization coefficient increased

Increasing the regularization coefficient  $c_\Psi$ :



(a) Grid size  $\Delta x = 50$  [m]

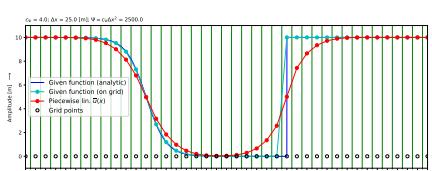


(b) Second derivatives, normalized grid size  
 $\Delta \xi = 1$ .

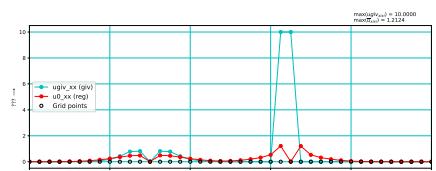
**Figure 4.12:** Regularization coefficient increased to 16 ( $c_\Psi = 16, \Delta x = 50$  [m])

### Grid size decreased

Decrease the grid size  $\Delta x$ :



(a) Step at grid node,  $c_\Psi = 4, \Delta x = 25$  [m]



(b) Second derivatives.

**Figure 4.13:** Grid size decreased to 25 [m] ( $c_\Psi = 4, \Delta x = 25$  [m])

## 4.4 Compatible initialization in one dimension

To assure that the given initial condition(s) are compatible with the numerical scheme, the given function need to fulfill the follow equation:

$$\int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \bar{u}_{initial} dx = \int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} u_{given} dx \quad (4.38)$$

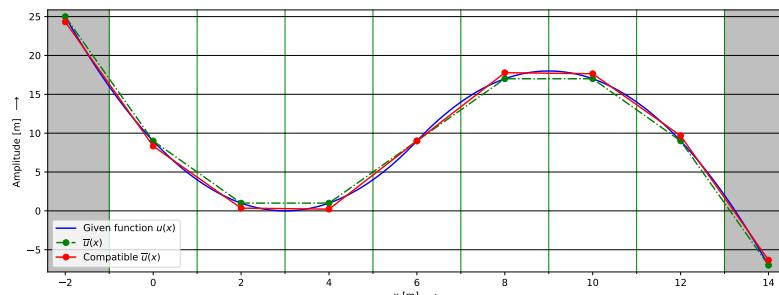
where  $\bar{u}$  is the piecewise linear function and  $u_{given}$  the given initial condition. In case the function  $u_{given}$  is an integrable analytic function the integral can be exact computed. In discrete form the equation for each control volume reads:

$$\frac{\Delta x_{i-\frac{1}{2}}}{2} \frac{u_{i-1} + 3u_i}{4} + \frac{\Delta x_{i+\frac{1}{2}}}{2} \frac{3u_i + u_{i+1}}{4} = \int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} u_{given} dx \quad (4.39)$$

Extra equations are needed for the boundary conditions, the following boundary treatment is used at  $x = 0$  (see section 4.1.2):

$$\frac{1}{12}u_0 + \frac{10}{12}u_1 + \frac{1}{12}u_2 = u_{given}(0) \quad (4.40)$$

and similar at the other boundary ( $x = 12$ ). An illustration off the result of equation (4.42) is given in Figure 4.14.



**Figure 4.14:** Illustration of compatible quadratic function. The integral over the control volume of the the given function (blue) is equal represented by the red-function and better then by the green-function, therefor the red function is called compatible with the given function. The green-function is defined with nodes on the given function. Control volumes shown by the green vertical lines. And the gray areas are virtual and are not belonging to the water body (see Figure 4.1).

Some numerical items used to generate Figure 4.14 are  $x \in [0, 12]$ ,  $\Delta x = 2$  and the given function reads:

$$u_{given}(x) = \begin{cases} (x - 3)^2 & x < 6 \\ -(x - 3)^2 + 18 & x \geq 6 \end{cases} \quad (4.41)$$

## 4.5 Compatible initialization in two dimensions

To assure that the given initial condition(s) are compatible with the numerical scheme, the given function need to fulfill the follow equation for each control volume:

$$\int_{y_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \int_{y_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \bar{u}_{initial} dx dy = \int_{y_{i-\frac{1}{2}}}^{y_{i+\frac{1}{2}}} \int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} u_{given} dx dy \quad (4.42)$$

where  $\bar{u}$  is the piecewise linear function and  $u_{given}$  the given initial condition. See for an example [Figure 4.4](#), when the function  $u_{given}$  is constructed by an interpolation method (triangulation, ...) between the dots. In case the function  $u_{given}$  is an integrable analytic function the integral can be exact computed.

On a structured grid one control volume ( $cv$ ) around a node consist of four sub-control volumes ( $scv_i, i \in \{1, 2, 3, 4\}$ ).

$$\begin{aligned} & \int_{scv_1} \bar{u}_{initial} d\omega + \int_{scv_2} \bar{u}_{initial} d\omega + \int_{scv_3} \bar{u}_{initial} d\omega + \int_{scv_4} \bar{u}_{initial} d\omega = \\ &= \int_{scv_1} u_{given} d\omega + \int_{scv_2} u_{given} d\omega + \int_{scv_3} u_{given} d\omega + \int_{scv_4} u_{given} d\omega \end{aligned} \quad (4.43)$$

Considering one sub-control volume,  $scv_3$ , and assuming a cartesian grid then the discrete form reads :

$$A_{scv_3} \bar{u}_{qp} = \int_{scv_3} u_{given} d\omega \quad (4.44)$$

with  $A_{scv_3} \approx \Delta x_{qp} \Delta y_{qp}$  the area of sub-control volume  $scv_3$ , with

$$\Delta x_{qp} = \frac{1}{2} \left[ \frac{1}{4} (3(x_{i+1,j} - x_{i,j}) + 1(x_{i+1,j+1} - x_{i,j+1})) \right], \quad (4.45)$$

$$\Delta y_{qp} = \frac{1}{2} \left[ \frac{1}{4} (3(y_{i+1,j} - y_{i,j}) + 1(y_{i+1,j+1} - y_{i,j+1})) \right], \quad (4.46)$$

$$\bar{u}_{qp} = \frac{1}{16} (9u_{i,j} + 3u_{i+1,j} + 3u_{i,j+1} + u_{i+1,j+1}). \quad (4.47)$$

# **1D Wave**

## 5 Towards the shallow water equations

Consider the non-linear wave equation when the pressure gradient is explicitly expressed as the gradient of the water level ( $\zeta$ ):

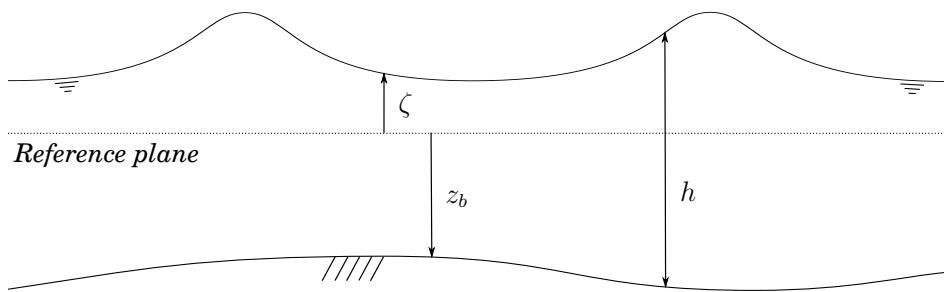
$$\underbrace{\frac{\partial h}{\partial t}}_{\text{Time derivative}} + \underbrace{\frac{\partial q}{\partial x}}_{\text{Mass flux}} = 0, \quad (5.1a)$$

$$\begin{aligned} & \underbrace{\frac{\partial q}{\partial t}}_{\text{Time derivative}} + \underbrace{\frac{\partial q^2/h}{\partial x}}_{\text{Convection}} + \underbrace{gh \frac{\partial \zeta}{\partial x}}_{\text{Pressure gradient}} + \\ & + \underbrace{c_f \frac{q|q|}{h^2}}_{\text{Bed shear stress}} - \underbrace{\frac{\partial}{\partial x} \left( \nu h \frac{\partial q/h}{\partial x} \right)}_{\text{Viscosity}} = 0, \end{aligned} \quad (5.1b)$$

$$\zeta = h + z_b \quad (5.1c)$$

with

$h$	Total water depth ( $h = \zeta - z_b$ ), [m].
$z_b$	Bed level w.r.t. reference plane, positive upward, [m].
$q$	Flow ( $q = hu$ ), [ $\text{m}^2 \text{s}^{-1}$ ].
$\zeta$	Water level w.r.t. reference plane ( $\zeta = h + z_b$ ), positive upward, [m].
$u$	Velocity ( $u = q/h$ ), [ $\text{m s}^{-1}$ ].
$g$	Acceleration due to gravity, [ $\text{m s}^{-2}$ ].
$\nu$	Kinematic viscosity, [ $\text{m}^2 \text{s}^{-1}$ ].



**Figure 5.1:** Definition sketch of water level ( $\zeta$ ), bed level ( $z_b$ ) and total water depth ( $h$ )

If  $u$  is needed for other processes (like morphology and/or post processing) it can be computed according the next equation:

$$u = \frac{q}{h}. \quad (5.2)$$

In the finite volume approach these equations read:

$$\int_{\Omega} \frac{\partial h}{\partial t} d\omega + \int_{\Omega} \frac{\partial q}{\partial x} d\omega = 0, \quad (5.3a)$$

$$\begin{aligned} \int_{\Omega} \frac{\partial q}{\partial t} d\omega + \int_{\Omega} \frac{\partial q^2/h}{\partial x} d\omega + \int_{\Omega} gh \frac{\partial \zeta}{\partial x} d\omega + \\ + \int_{\Omega} c_f \frac{q|q|}{h^2} d\omega - \int_{\Omega} \frac{\partial}{\partial x} \left( \nu h \frac{\partial q/h}{\partial x} \right) d\omega = 0, \end{aligned} \quad (5.3b)$$

$$\int_{\Omega} \zeta d\omega = \int_{\Omega} h d\omega + \int_{\Omega} z_b d\omega \quad (5.3c)$$

In this document we will end up with an implementation description of the 1D shallow water equation. We start a zero-dimensional implementation of a source term, representing the source and sink of external influences, like a power plant. Here we will show the results of a Brusselator ([Ault and Holmgreen, 2003](#)) and of a air pollution model ([Hundsdorfer and Verwer, 2003, ex. 1.1 pg. 7](#)). Then we continue with the one dimensional advection/transport equation than a one dimensional wave equation without convection, then with convection and at last with a bottom friction term. in this sequence we are missing the viscosity term, that term will be investigated by the advection-diffusion equation.

Because we will handle the shallow water equations in the variables  $h$  and  $q$  and not in  $\zeta$  and  $u$  the equations does have always a non-linear behaviour, only for very small amplitude the behaviour is like a linear system. For linear wave equations the behaviour is always linear, even for large amplitudes, which is not the case for the equations we consider.

## 5.1 0-D Source/sink term

In this section a zero-dimensional model is implementation of the source term, representing the source and sink of external influences, like a power plant. The main (simple) equation will look like:

$$\frac{\partial u}{\partial t} = f(u, t) \quad (5.4)$$

Here we will show the mathematical and implementation of an air pollution model, [section 5.1.1](#) ([Hundsdorfer and Verwer, 2003, ex. 1.1 pg. 7](#)) and a Brusselator, [section 5.1.2](#) ([Ault and Holmgreen, 2003](#)). Some results are shown in [section 6.1](#).

### 5.1.1 Air pollution

### Analytic description

We illustrate the mass action law by the following three reactions between oxygen  $O_2$ , atomic oxygen  $O$ , nitrogen oxide  $NO$ , and nitrogen dioxide  $NO_2$  ([Hundsorfer and Verwer, 2003](#), eq. 1.1, page 7):



These reactions are basic to any tropospheric air pollution model. The first-reaction is photochemical and says that  $NO$  and  $O$  are formed from  $NO_2$  by photo-dissociation caused by solar radiation, indicated by  $h\nu$ . This depends on the time of the day and therefore  $k_l = k_l(t)$ . We consider the concentrations  $u_1 = [O]$ ,  $u_2 = [NO]$ ,  $u_3 = [NO_2]$ ,  $u_4 = [O_3]$ . The oxygen concentration  $[O_2]$  is treated as constant, and we assume there is a constant source term  $\sigma_2$  simulating emission of nitrogen oxide. The rate functions and stoichiometric matrix are

$$g(t, u) = \begin{pmatrix} k_1(t)u_3 \\ k_2u_1 \\ k_3u_2u_4 \end{pmatrix}, \quad S = \begin{pmatrix} 1 & -1 & 0 \\ 1 & 0 & -1 \\ -1 & 0 & 1 \\ 0 & 1 & -1 \end{pmatrix} \quad (5.8)$$

The corresponding ODE system reads:

$$\frac{\partial u_1}{\partial t} = k_1 u_3 - k_2 u_1 \quad (5.9)$$

$$\frac{\partial u_2}{\partial t} = k_1 u_3 - k_3 u_2 u_4 + \sigma_2 \quad (5.10)$$

$$\frac{\partial u_3}{\partial t} = k_3 u_2 u_4 - k_1 u_3 \quad (5.11)$$

$$\frac{\partial u_4}{\partial t} = k_2 u_1 - k_3 u_2 u_4 \quad (5.12)$$

We see that

$$\frac{\partial u_1}{\partial t} + \frac{\partial u_3}{\partial t} + \frac{\partial u_4}{\partial t} = 0, \quad (5.13)$$

and

$$\frac{\partial u_2}{\partial t} + \frac{\partial u_3}{\partial t} = \sigma_2 t \quad (5.14)$$

hence  $[O] + [NO_2] + [O_3]$  is a conserved quantity while  $[NO] + [NO_2]$  grows with  $\sigma_2 t$ . By considering the null-space of  $S^T$  it is seen that these are the two mass laws for this chemical model.

With  $\mathbf{u}(0) = (0.0, 2.0 \times 10^{-1}, 2.0 \times 10^{-3}, 2.0 \times 10^{-1})^T$  and  $\sigma_2 = 10^{-7}$ , and the coefficients  $k$  are defined as (this given conditions are different from the conditions as defined in [Hundsdorfer and Verwer \(2003, pg. 8\)](#):

$$k_1 = \begin{cases} 10^{-5} \exp(7g(t)) \\ 10^{-40}, \quad \text{during night} \end{cases} \quad (5.15)$$

$$k_2 = 2.0 \times 10^{-2} \quad (5.16)$$

$$k_3 = 1.0 \times 10^{-3} \quad (5.17)$$

with

$$g(t) = \left( \sin\left(\frac{\pi}{16}(t_h - 4)\right) \right)^{0.2}, \quad t_h = \frac{t}{3600}; \quad (5.18)$$

where  $t_h$  is the time in hours. How these equations are discretized is given in [equation \(5.1.1\)](#).

### Numerical discretization

The discretization in  $\Delta$ -formulation reads:

$$\frac{1}{\Delta t} \Delta u_1^{n+1,p+1} = -\frac{1}{\Delta t} (u_1^{n+1,p} - u_1^n) + k_1(u_3^{n+\theta,p+1}) - k_2(u_1^{n+\theta,p+1}) \quad (5.19)$$

$$\frac{1}{\Delta t} \Delta u_2^{n+1,p+1} = -\frac{1}{\Delta t} (u_2^{n+1,p} - u_2^n) + k_1(u_3^{n+\theta,p+1}) - k_3(u_2^{n+\theta,p+1})(u_4^{n+\theta,p+1}) + \sigma_2 \quad (5.20)$$

$$\frac{1}{\Delta t} \Delta u_3^{n+1,p+1} = -\frac{1}{\Delta t} (u_3^{n+1,p} - u_3^n) + k_3(u_2^{n+\theta,p+1})(u_4^{n+\theta,p+1}) - k_1(u_3^{n+\theta,p+1}) \quad (5.21)$$

$$\frac{1}{\Delta t} \Delta u_4^{n+1,p+1} = -\frac{1}{\Delta t} (u_4^{n+1,p} - u_4^n) + k_2(u_1^{n+\theta,p+1}) - k_3(u_2^{n+\theta,p+1})(u_4^{n+\theta,p+1}) \quad (5.22)$$

with linearization of  $\mathbf{u}^{n+\theta,p+1}$  yields:

$$\begin{aligned} \frac{1}{\Delta t} \Delta u_1^{n+1,p+1} &= -\frac{1}{\Delta t} (u_1^{n+1,p} - u_1^n) + \\ &+ k_1(u_3^{n+\theta,p} + \theta \Delta u_3^{n+1,p+1}) - k_2(u_1^{n+\theta,p} + \theta \Delta u_1^{n+1,p+1}) \end{aligned} \quad (5.23)$$

$$\begin{aligned} \frac{1}{\Delta t} \Delta u_2^{n+1,p+1} &= -\frac{1}{\Delta t} (u_2^{n+1,p} - u_2^n) + k_1(u_3^{n+\theta,p} + \theta \Delta u_3^{n+1,p+1}) + \\ &- k_3(u_2^{n+\theta,p} + \theta \Delta u_2^{n+1,p+1})(u_4^{n+\theta,p} + \theta \Delta u_4^{n+1,p+1}) + \sigma_2 \end{aligned} \quad (5.24)$$

$$\begin{aligned} \frac{1}{\Delta t} \Delta u_3^{n+1,p+1} &= -\frac{1}{\Delta t} (u_3^{n+1,p} - u_3^n) + k_3(u_2^{n+\theta,p} + \theta \Delta u_2^{n+1,p+1})(u_4^{n+\theta,p} + \\ &+ \theta \Delta u_4^{n+1,p+1}) - k_1(u_3^{n+\theta,p} + \theta \Delta u_3^{n+1,p+1}) \end{aligned} \quad (5.25)$$

$$\begin{aligned} \frac{1}{\Delta t} \Delta u_4^{n+1,p+1} &= -\frac{1}{\Delta t} (u_4^{n+1,p} - u_4^n) + k_2(u_1^{n+\theta,p} + \theta \Delta u_1^{n+1,p+1}) + \\ &- k_3(u_2^{n+\theta,p} + \theta \Delta u_2^{n+1,p+1})(u_4^{n+\theta,p} + \theta \Delta u_4^{n+1,p+1}) \end{aligned} \quad (5.26)$$

and rearrange the system of equations to  $\mathbf{Ax} = \mathbf{b}$ , yields

$$\begin{aligned}\frac{1}{\Delta t} \Delta u_1^{n+1,p+1} - k_1 \theta \Delta u_3^{n+1,p+1} + k_2 \theta \Delta u_1^{n+1,p+1} &= \\ &= -\frac{1}{\Delta t} (u_1^{n+1,p} - u_1^n) + k_1 u_3^{n+\theta,p} - k_2 u_1^{n+\theta,p}\end{aligned}\quad (5.27)$$

$$\begin{aligned}\frac{1}{\Delta t} \Delta u_2^{n+1,p+1} - k_1 \theta \Delta u_3^{n+1,p+1} + k_3 \theta u_4^{n+1,p} \Delta u_2^{n+1,p+1} + k_3 \theta u_2^{n+1,p} \Delta u_4^{n+1,p+1} &= \\ &= -\frac{1}{\Delta t} (u_2^{n+1,p} - u_2^n) + k_1 u_3^{n+\theta,p} - k_3 u_2^{n+\theta,p} u_4^{n+\theta,p} + \sigma_2\end{aligned}\quad (5.28)$$

$$\begin{aligned}\frac{1}{\Delta t} \Delta u_3^{n+1,p+1} - k_3 u_2^{n+\theta,p} \theta \Delta u_4^{n+1,p+1} - k_3 u_4^{n+\theta,p} \theta \Delta u_2^{n+1,p+1} + k_1 \theta \Delta u_3^{n+1,p+1} &= \\ &= -\frac{1}{\Delta t} (u_3^{n+1,p} - u_3^n) + k_3 u_2^{n+\theta,p} u_4^{n+\theta,p} - k_1 u_3^{n+\theta,p}\end{aligned}\quad (5.29)$$

$$\begin{aligned}\frac{1}{\Delta t} \Delta u_4^{n+1,p+1} - k_2 \theta \Delta u_1^{n+1,p+1} + k_3 u_2^{n+\theta,p} \theta \Delta u_4^{n+1,p+1} + k_3 u_4^{n+\theta,p} \theta \Delta u_2^{n+1,p+1} &= \\ &= -\frac{1}{\Delta t} (u_4^{n+1,p} - u_4^n) + k_2 u_1^{n+\theta,p} - k_3 u_2^{n+\theta,p} u_4^{n+\theta,p}\end{aligned}\quad (5.30)$$

## 5.1.2 Brusselator

### Analytic description

The ODE system for the Brusselator reads [Ault and Holmgreen \(2003, eq. 14, 15\)](#):

$$\frac{\partial u_1}{\partial t} = 1 - (k_2 + 1)u_1 + k_1 u_1^2 u_2, \quad (5.31)$$

$$\frac{\partial u_2}{\partial t} = k_2 u_1 - k_1 u_1^2 u_2 \quad (5.32)$$

with  $k_1 = 1$  and  $k_2 = 2.5$  and initial values  $u_1(0) = 0$  and  $u_2(0) = 0$ .

### Numerical discretization

The ODE system for the brusselator reads [\(Ault and Holmgreen, 2003, eq. 14, 15\)](#):

$$\frac{\partial u_1}{\partial t} = 1 - (k_2 + 1)u_1 + k_1 u_1^2 u_2, \quad (5.33)$$

$$\frac{\partial u_2}{\partial t} = k_2 u_1 - k_1 u_1^2 u_2 \quad (5.34)$$

The discretization in  $\Delta$ -formulation reads:

$$\begin{aligned}\frac{1}{\Delta t} \Delta u_1^{n+1,p+1} &= -\frac{1}{\Delta t} (u_1^{n+1,p} - u_1^n) + 1 - (k_2 + 1)u_1^{n+\theta,p+1} + \\ &\quad + k_1 \left( u_1^{n+\theta,p+1} \right)^2 u_2^{n+\theta,p+1}\end{aligned}\quad (5.35)$$

$$\begin{aligned}\frac{1}{\Delta t} \Delta u_2^{n+1,p+1} &= -\frac{1}{\Delta t} (u_2^{n+1,p} - u_2^n) + k_2 (u_1^{n+\theta,p+1}) + \\ &\quad - k_1 \left( u_1^{n+\theta,p+1} \right)^2 u_2^{n+\theta,p+1}\end{aligned}\quad (5.36)$$

with linearization of  $u^{n+\theta,p+1}$  yields:

$$\begin{aligned}\frac{1}{\Delta t} \Delta u_1^{n+1,p+1} &= -\frac{1}{\Delta t} (u_1^{n+1,p} - u_1^n) + 1 - (k_2 + 1) \left( u_1^{n+\theta,p} + \theta \Delta u_1^{n+1,p+1} \right) + \\ &\quad + k_1 \left( u_1^{n+\theta,p} + \Delta u_1^{n+1,p+1} \right)^2 \left( u_2^{n+\theta,p} + \Delta u_1^{n+1,p+1} \right)\end{aligned}\quad (5.37)$$

$$\begin{aligned}\frac{1}{\Delta t} \Delta u_2^{n+1,p+1} &= -\frac{1}{\Delta t} (u_2^{n+1,p} - u_2^n) + k_2 (u_1^{n+\theta,p} + \theta \Delta u_1^{n+1,p+1}) + \\ &\quad - k_1 \left( u_1^{n+\theta,p} + \Delta u_1^{n+1,p+1} \right)^2 \left( u_2^{n+\theta,p} + \Delta u_1^{n+1,p+1} \right)\end{aligned}\quad (5.38)$$

and rearrange the system of equations to  $\mathbf{Ax} = \mathbf{b}$  and omitting the second order terms, yields

$$\begin{aligned}\frac{1}{\Delta t} \Delta u_1^{n+1,p+1} - \theta \left( (k_2 + 1) + 2k_1 u_1^{n+\theta,p} u_2^{n+\theta,p} \right) \Delta u_1^{n+1,p+1} - \theta k_1 (u_1^{n+1,p+1})^2 \Delta u_2^{n+1,p+1} &= \\ = -\frac{1}{\Delta t} (u_1^{n+1,p} - u_1^n) + 1 - (k_2 + 1) u_1^{n+\theta,p} + k_1 (u_1^{n+\theta,p})^2 u_2^{n+\theta,p} &\quad (5.39)\end{aligned}$$

$$\begin{aligned}\frac{1}{\Delta t} \Delta u_2^{n+1,p+1} + \theta \left( k_2 + 2k_1 u_1^{n+\theta,p} u_2^{n+\theta,p} \right) \Delta u_1^{n+1,p+1} + \theta k_1 (u_1^{n+1,p+1})^2 \Delta u_2^{n+1,p+1} &= \\ = -\frac{1}{\Delta t} (u_2^{n+1,p} - u_2^n) + k_2 u_1^{n+\theta,p} - k_1 (u_1^{n+\theta,p})^2 u_2^{n+\theta,p} &\quad (5.40)\end{aligned}$$

This system can be implemented and solved, some results are presented in section 5.1.2.

## 5.2 1-D Advection-diffusion equation

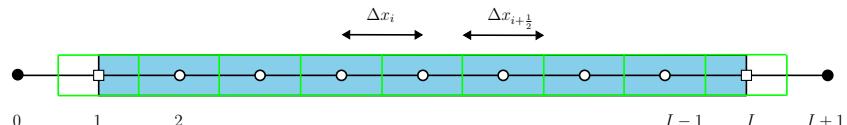
In this section we will discuss the discretization of an advection-diffusion equation when the constituent does not need to be positive and when the constituent must be positive.

### 5.2.1 Not strictly positive constituent

The considered advection-diffusion equation reads:

$$\frac{\partial c}{\partial t} + \frac{\partial u c}{\partial x} - \frac{\partial}{\partial x} \left( \varepsilon \frac{\partial c}{\partial x} \right) = 0, \quad u > 0. \quad (5.41)$$

A constituent  $c$  is transported from the left to the right with the constant velocity  $u$  [ $\text{m s}^{-1}$ ]. Which is discretised on the grid



**Figure 5.2:** Water body (blue area), finite volumes (green boxes), computational points (open dots), virtual computational points (black dots), boundary points are at  $x_1$  (inflow/west boundary) and  $x_{I+\frac{1}{2}}$  (outflow/east boundary).

The finite volume approach for control volume  $\Delta x_{i+\frac{1}{2}}$  of equation (5.41) reads:

$$\int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \frac{\partial c}{\partial t} dx + \int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \frac{\partial uc}{\partial x} dx - \int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \frac{\partial}{\partial x} \left( \varepsilon \frac{\partial c}{\partial x} \right) dx = 0 \quad (5.42)$$

$$\int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \frac{\partial c}{\partial t} dx + (uc)|_{i+\frac{1}{2}} - (uc)|_{i-\frac{1}{2}} - \left( \varepsilon \frac{\partial c}{\partial x} \Big|_{i+\frac{1}{2}} - \varepsilon \frac{\partial c}{\partial x} \Big|_{i-\frac{1}{2}} \right) = 0 \quad (5.43)$$

### Discretization interior

The discretization in  $\Delta$ -formulation in the interior of domain  $\Omega$  and for equidistant grid and the mass-matrix as given in equation (3.6) reads

$$\begin{aligned} & \Delta x \Delta t_{inv} \left( \frac{1}{8} \Delta c_{i-1}^{n+1,p+1} + \frac{6}{8} \Delta c_i^{n+1,p+1} + \frac{1}{8} \Delta c_{i+1}^{n+1,p+1} \right) + \\ & + \left\{ \Delta x \Delta t_{inv} \left( \frac{1}{8} (c_{i-1}^{n+1,p} - c_{i-1}^n) + \frac{6}{8} (c_i^{n+1,p} - c_i^n) + \frac{1}{8} (c_{i+1}^{n+1,p} - c_{i+1}^n) \right) \right\} + \\ & + u \left( \frac{1}{2} (c_i^{n+\theta,p+1} + c_{i+1}^{n+\theta,p+1}) - \frac{1}{2} (c_{i-1}^{n+\theta,p+1} + c_i^{n+\theta,p+1}) \right) + \\ & - \left( \varepsilon_{i+\frac{1}{2}} \frac{c_{i+1}^{n+\theta,p+1} - c_i^{n+\theta,p+1}}{\Delta x} - \varepsilon_{i-\frac{1}{2}} \frac{c_i^{n+\theta,p+1} - c_{i-1}^{n+\theta,p+1}}{\Delta x} \right) = 0 \end{aligned} \quad (5.44)$$

After linearization of  $c^{n+\theta,p+1}$  the discretization reads:

$$\begin{aligned} & \Delta x \Delta t_{inv} \left( \frac{1}{8} \Delta c_{i-1}^{n+1,p+1} + \frac{6}{8} \Delta c_i^{n+1,p+1} + \frac{1}{8} \Delta c_{i+1}^{n+1,p+1} \right) \\ & + \frac{1}{2} \theta u (\Delta c_i^{n+1,p+1} + \Delta c_{i+1}^{n+1,p+1} - (\Delta c_{i-1}^{n+1,p+1} + \Delta c_i^{n+1,p+1})) + \\ & - \theta \frac{\varepsilon_{i+\frac{1}{2}}}{\Delta x} \Delta c_{i+1}^{n+1,p+1} + \theta \left( \frac{\varepsilon_{i+\frac{1}{2}}}{\Delta x} + \frac{\varepsilon_{i-\frac{1}{2}}}{\Delta x} \right) \Delta c_i^{n+1,p+1} - \theta \frac{\varepsilon_{i-\frac{1}{2}}}{\Delta x} \Delta c_{i-1}^{n+1,p+1} = \\ & = - \left\{ \Delta x \Delta t_{inv} \left( \frac{1}{8} (c_{i-1}^{n+1,p} - c_{i-1}^n) + \frac{6}{8} (c_i^{n+1,p} - c_i^n) + \frac{1}{8} (c_{i+1}^{n+1,p} - c_{i+1}^n) \right) + \right. \\ & + \frac{1}{2} u \left( (c_i^{n+\theta,p} + c_{i+1}^{n+\theta,p}) - (c_{i-1}^{n+\theta,p} + c_i^{n+\theta,p}) \right) + \\ & \left. - \left( \varepsilon_{i+\frac{1}{2}} \frac{c_{i+1}^{n+\theta,p} - c_i^{n+\theta,p}}{\Delta x} - \varepsilon_{i-\frac{1}{2}} \frac{c_i^{n+\theta,p} - c_{i-1}^{n+\theta,p}}{\Delta x} \right) \right\} \end{aligned} \quad (5.45)$$

### Discretization at boundaries

An **essential** boundary condition at the inflow boundary is needed, left side of the domain. And, at the right side an outflow boundary 'condition' is required for numerical reasons (called a **natural** boundary condition), i.e. a discretization of the model equation at the outflow boundary. The natural boundary conditions is fully determined by the outgoing signal and therefor we use the equation of the outgoing signal, i.e. equation (5.59). For the 1-D advection-diffusion

equation when omitting the viscosity term it reads:

$$\frac{\partial c}{\partial t} + \frac{\partial u c}{\partial x} = 0, \quad u > 0. \quad (5.46)$$

The **essential** boundary condition at the inflow boundary reads:

$$c(0, t) = c_0(t), \quad t > 0 \quad (\text{essential boundary}) \quad (5.47)$$

The essential boundary condition is supplied at  $x_1$  with the following discretization (equation (4.10))

$$\begin{aligned} \frac{1}{12} \Delta c_0^{n+1,p+1} + \frac{10}{12} \Delta c_1^{n+1,p+1} + \frac{1}{12} \Delta c_2^{n+1,p+1} = \\ = c_0(t) - \left( \frac{1}{12} c_0^{n+1,p} + \frac{10}{12} c_1^{n+1,p} + \frac{1}{12} c_2^{n+1,p} \right) \end{aligned} \quad (5.48)$$

**TODO 5.1:** *The implementation is not stable, check implementation!*

**TODO**

The **natural** is chosen in that way that as less as possible left going spurious numerical waves are generated at the outflow boundary, i.e. nearly no reflection. The natural boundary condition is supplied at  $x_I$  with the discretization constants as determined by equation (4.9) and boundary condition equation (5.46) which yields:

$$\left( \frac{1 + \alpha_{bnd}}{\Delta t} + \theta \frac{u}{\Delta x} \right) \Delta c_{I+1}^{n+1,p+1} + \left( \frac{1 - 2\alpha_{bnd}}{\Delta t} - \theta \frac{u}{\Delta x} \right) \Delta c_I^{n+1,p+1} + \frac{\alpha_{bnd}}{\Delta t} \Delta c_{I-1}^{n+1,p+1} =$$

$$(5.49)$$

$$= - \left\{ \frac{1 + \alpha_{bnd}}{\Delta t} (c_{I+1}^{n+1,p} - c_{I+1}^n) + \frac{1 - 2\alpha_{bnd}}{\Delta t} (c_I^{n+1,p} - c_I^n) + \frac{\alpha_{bnd}}{\Delta t} (c_{I-1}^{n+1,p} - c_{I-1}^n) + \right.$$

$$(5.50)$$

$$\left. + \frac{u}{\Delta x} (c_{I+1}^{n+\theta,p} - c_I^{n+\theta,p}) \right\}$$

$$(5.51)$$

where  $\alpha_{bnd} = 2\alpha - \frac{1}{2}$  ( $\alpha_{bnd} = -\frac{1}{4}$  when  $\alpha = \frac{1}{8}$ ).

## 5.2.2 Strictly positive constituent

When  $c$  needs a strictly positive value (like a concentration) then due to numerical discretization the value  $c$  could become negative, even if the initial and boundary values are positive. In certain applications a positive value is required and even small negative are not allowed. To ensure the positivity of the constituent  $c$  we will write the equation with variable  $\phi$ , where  $\phi$  is defined as:

$$c = \exp(\ln(c)) = \exp(\phi), \quad \text{with } \phi = \ln(c) \quad (5.52)$$

The considered advection-diffusion equation than reads:

$$\int_{\Omega} \frac{\partial e^{\phi}}{\partial t} d\omega + \int_{\Omega} \frac{\partial (ue^{\phi})}{\partial x} d\omega - \int_{\Omega} \frac{\partial}{\partial x} \left( \varepsilon \frac{\partial e^{\phi}}{\partial x} \right) d\omega = 0, \quad (5.53)$$

### *Discretization interior*

**Not yet documented**

### *Discretization at boundaries*

**Not yet documented**

## 5.3 1-D Wave equation

The hyperbolic part of the one dimensional shallow water equations (assuming that the viscosity term vanish) are diagonalized to separate the left and right going wave. We start from the following equations, with convection for flat bottom ( $\frac{1}{2}g \partial h^2 / \partial x = gh \partial h / \partial x$  and  $\partial z_b / \partial x = 0$ ), reads

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = 0 \quad \text{continuity eq.} \quad (5.54)$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q^2}{h} \right) + gh \frac{\partial h}{\partial x} = 0 \quad \text{momentum eq.} \quad (5.55)$$

These one dimensional shallow water equations can be written in matrix and vector notation as:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{A} \frac{\partial \mathbf{u}}{\partial x} = 0 \quad (5.56)$$

To find the characteristic equations this set of equations should be written in a set of equation representing left and right going waves. The diagonalisation is performed as follows:

$$\frac{\partial \mathbf{u}}{\partial t} + \underbrace{\mathbf{P} \mathbf{P}^{-1} \mathbf{A} \mathbf{P} \mathbf{P}^{-1}}_{\Lambda} \frac{\partial \mathbf{u}}{\partial x} = 0 \quad (5.57)$$

multiply this with  $\mathbf{P}^{-1}$

$$\mathbf{P}^{-1} \frac{\partial \mathbf{u}}{\partial t} + \Lambda \mathbf{P}^{-1} \frac{\partial \mathbf{u}}{\partial x} = 0 \quad (5.58)$$

with  $\Lambda$  a diagonal matrix and thus the left and right going signals are independent. For the one dimensional shallow water equations the two independent equations read:

$$\begin{array}{ll} \text{right going} & \begin{pmatrix} \sqrt{gh} + \frac{q}{h} & -1 \\ \sqrt{gh} - \frac{q}{h} & 1 \end{pmatrix} \begin{pmatrix} \text{continuity eq.} \\ \text{momentum eq.} \end{pmatrix} = 0 \\ \text{left going} & \end{array} \quad (5.59)$$

See for a derivation [Appendix C](#).

We have split the hyperbolic wave equation into a right and left going wave. Now we are able to apply the **natural** boundary conditions as described in section 5.2.1 for each of the waves. The **essential** boundary condition is chosen to be an absorbing boundary, so no reflections at the boundaries will appear.

For the space discretizations of an arbitrary function  $u$ , the following space interpolations are used:

$$u_{i+\frac{1}{2}} = \frac{1}{2} (u_{i+1} + u_i) \quad \text{interface of control volume} \quad (5.60)$$

$$u_{i+\frac{1}{4}} = \frac{1}{4} (3u_i + u_{i+1}) \quad \text{quadrature point of sub-control volume} \quad (5.61)$$

$$u_{i-\frac{1}{4}} = \frac{1}{4} (3u_i + u_{i-1}) \quad \text{quadrature point of sub-control volume} \quad (5.62)$$

These formulas are visualized in Figure 4.3.

### 5.3.1 Discretizations continuity equation

The discretization of the continuity equation will be presented term by term of equation (5.54).

#### 5.3.1.1 Time derivative

The discretization of the time derivative term of the continuity equation reads:

$$\int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \frac{\partial h}{\partial t} dx \quad (5.63)$$

which will be approximated by

$$\begin{aligned} & \frac{1}{2} \Delta x_{i-\frac{1}{2}} \left( \frac{1}{4} \frac{\partial h_{i-1}}{\partial t} + \frac{3}{4} \frac{\partial h_i}{\partial t} \right) + \frac{1}{2} \Delta x_{i+\frac{1}{2}} \left( \frac{3}{4} \frac{\partial h_i}{\partial t} + \frac{1}{4} \frac{\partial h_{i+1}}{\partial t} \right) \approx \\ & \approx \frac{1}{2} \frac{\Delta x_{i-\frac{1}{2}}}{\Delta t} \left( \frac{1}{4} (\Delta h_{i-1}^{n+1,p+1} + h_{i-1}^{n+1,p} - h_{i-1}^n) + \frac{3}{4} (\Delta h_i^{n+1,p+1} + h_i^{n+1,p} - h_i^n) \right) + \\ & + \frac{1}{2} \frac{\Delta x_{i+\frac{1}{2}}}{\Delta t} \left( \frac{3}{4} (\Delta h_i^{n+1,p+1} + h_{i+1}^{n+1,p} - h_i^n) + \frac{1}{4} (\Delta h_{i+1}^{n+1,p+1} + h_{i+1}^{n+1,p} - h_{i+1}^n) \right) \end{aligned} \quad (5.64)$$

after rearranging the equation into an implicit left hand side and an explicit right hand side it reads:

$$\begin{aligned} & \frac{1}{2} \frac{\Delta x_{i-\frac{1}{2}}}{\Delta t} \left( \frac{1}{4} \Delta h_{i-1}^{n+1,p+1} + \frac{3}{4} \Delta h_i^{n+1,p+1} \right) + \frac{1}{2} \frac{\Delta x_{i+\frac{1}{2}}}{\Delta t} \left( \frac{3}{4} \Delta h_i^{n+1,p+1} + \frac{1}{4} \Delta h_{i+1}^{n+1,p+1} \right) = \\ & = - \left\{ \frac{1}{2} \frac{\Delta x_{i-\frac{1}{2}}}{\Delta t} \left( \frac{1}{4} (h_{i-1}^{n+1,p} - h_{i-1}^n) + \frac{3}{4} (h_i^{n+1,p} - h_i^n) \right) + \right. \\ & \left. + \frac{1}{2} \frac{\Delta x_{i+\frac{1}{2}}}{\Delta t} \left( \frac{3}{4} (h_{i+1}^{n+1,p} - h_i^n) + \frac{1}{4} (h_{i+1}^{n+1,p} - h_{i+1}^n) \right) \right\} \end{aligned} \quad (5.65)$$

### 5.3.1.2 Mass flux

The discretization of the mass flux term of the continuity equation reads:

$$\int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \frac{\partial q}{\partial x} dx \quad (5.66)$$

which will be approximated by the  $\theta$ -method and using Green's theorem:

$$q_{i+\frac{1}{2}}^{n+\theta,p+1} - q_{i-\frac{1}{2}}^{n+\theta,p+1}. \quad (5.67)$$

The linearization of the flux  $q$  around iteration level  $p$  reads then:

$$q_{i+\frac{1}{2}}^{n+\theta,p} + \theta \Delta q_{i+\frac{1}{2}}^{n+1,p+1} - q_{i-\frac{1}{2}}^{n+\theta,p} - \theta \Delta q_{i-\frac{1}{2}}^{n+1,p+1} \quad (5.68)$$

after rearranging the equation into an implicit left hand side and an explicit right hand side it reads:

$$\frac{1}{2} \theta \Delta q_i^{n+1,p+1} - \frac{1}{2} \theta \Delta q_{i-1}^{n+1,p+1} + \left\{ \frac{1}{2} q_{i+1}^{n+\theta,p} - \frac{1}{2} q_{i-1}^{n+\theta,p} \right\} \quad (5.69)$$

### 5.3.2 Discretizations momentum equation

The discretization of the momentum equation will be presented term by term of [equation \(5.55\)](#).

#### 5.3.2.1 Time derivative

The discretization of the time derivative term of the momentum equation reads and is similar as for the continuity equation:

$$\int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \frac{\partial q}{\partial t} dx \quad (5.70)$$

which will be approximated by

$$\begin{aligned} & \frac{1}{2} \Delta x_{i-\frac{1}{2}} \left( \frac{1}{4} \frac{\partial q_{i-1}}{\partial t} + \frac{3}{4} \frac{\partial q_i}{\partial t} \right) + \frac{1}{2} \Delta x_{i+\frac{1}{2}} \left( \frac{3}{4} \frac{\partial q_i}{\partial t} + \frac{1}{4} \frac{\partial q_{i+1}}{\partial t} \right) \approx \\ & \approx \frac{1}{2} \frac{\Delta x_{i-\frac{1}{2}}}{\Delta t} \left( \frac{1}{4} (\Delta q_{i-1}^{n+1,p+1} + q_{i-1}^{n+1,p} - q_{i-1}^n) + \frac{3}{4} (\Delta q_i^{n+1,p+1} + q_i^{n+1,p} - h_i^n) \right) + \\ & + \frac{1}{2} \frac{\Delta x_{i+\frac{1}{2}}}{\Delta t} \left( \frac{3}{4} (\Delta q_i^{n+1,p+1} + q_{i+1}^{n+1,p} - q_i^n) + \frac{1}{4} (\Delta q_{i+1}^{n+1,p+1} + q_{i+1}^{n+1,p} - q_{i+1}^n) \right) \end{aligned} \quad (5.71)$$

after rearranging the equation into an implicit left hand side and an explicit right hand side it reads:

$$\begin{aligned} & \frac{1}{2} \frac{\Delta x_{i-\frac{1}{2}}}{\Delta t} \left( \frac{1}{4} \Delta q_{i-1}^{n+1,p+1} + \frac{3}{4} \Delta q_i^{n+1,p+1} \right) + \frac{1}{2} \frac{\Delta x_{i+\frac{1}{2}}}{\Delta t} \left( \frac{3}{4} \Delta q_i^{n+1,p+1} + \frac{1}{4} \Delta q_{i+1}^{n+1,p+1} \right) + \\ & + \left\{ \frac{1}{2} \frac{\Delta x_{i-\frac{1}{2}}}{\Delta t} \left( \frac{1}{4} (q_{i-1}^{n+1,p} - q_{i-1}^n) + \frac{3}{4} (q_i^{n+1,p} - q_i^n) \right) + \right. \\ & \left. + \frac{1}{2} \frac{\Delta x_{i+\frac{1}{2}}}{\Delta t} \left( \frac{3}{4} (q_{i+1}^{n+1,p} - q_i^n) + \frac{1}{4} (q_{i+1}^{n+1,p} - q_{i+1}^n) \right) \right\} \end{aligned} \quad (5.72)$$

### 5.3.2.2 Pressure term

The pressure term is dependent on the gradient of the water level  $\zeta$  and reads:

$$\int_{i-\frac{1}{2}}^{i+\frac{1}{2}} gh \frac{\partial \zeta}{\partial x} dx. \quad (5.73)$$

The acceleration due to gravity is assumed to be constant ( $g = \text{constant}$ ). We first linearize the equation and then discretize in space. The linearization of the pressure term around iteration level  $p$  reads:

$$gh \frac{\partial \zeta}{\partial x} \Big|^{n+\theta,p+1} \approx \quad (5.74)$$

$$\approx gh^{n+\theta,p} \frac{\partial \zeta^{n+\theta,p}}{\partial x} + g \frac{\partial \zeta^{n+\theta,p}}{\partial x} \theta \Delta h^{n+1,p+1} + gh^{n+\theta,p} \frac{\partial}{\partial x} \theta \Delta \zeta^{n+1,p+1} \quad (5.75)$$

Computing the integral over the finite volume:

$$\int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} gh \frac{\partial \zeta}{\partial x} dx = \int_{x_{i-\frac{1}{2}}}^{x_i} gh \frac{\partial \zeta}{\partial x} dx + \int_{x_i}^{x_{i+\frac{1}{2}}} gh \frac{\partial \zeta}{\partial x} dx \quad (5.76)$$

with piecewise linear  $h$  en piecewise linear  $\zeta$ , thus piecewise constant  $\partial \zeta / \partial x$ .

The first term of [equation \(5.75\)](#) becomes:

$$\begin{aligned} & \int_{x_{i-\frac{1}{2}}}^{x_i} gh^{n+\theta,p} \frac{\partial \zeta^{n+\theta,p}}{\partial x} dx + \int_{x_i}^{x_{i+\frac{1}{2}}} gh^{n+\theta,p} \frac{\partial \zeta^{n+\theta,p}}{\partial x} dx \approx \\ & \approx \frac{\Delta x_{i-\frac{1}{2}}}{2} gh_{i-\frac{1}{4}}^{n+\theta,p} \frac{\zeta_i^{n+\theta,p} - \zeta_{i-1}^{n+\theta,p}}{\Delta x_{i-\frac{1}{2}}} + \frac{\Delta x_{i+\frac{1}{2}}}{2} gh_{i+\frac{1}{4}}^{n+\theta,p} \frac{\zeta_{i+1}^{n+\theta,p} - \zeta_i^{n+\theta,p}}{\Delta x_{i+\frac{1}{2}}} \end{aligned} \quad (5.77)$$

$$= \frac{1}{2} gh_{i-\frac{1}{4}}^{n+\theta,p} (\zeta_i^{n+\theta,p} - \zeta_{i-1}^{n+\theta,p}) + \frac{1}{2} gh_{i+\frac{1}{4}}^{n+\theta,p} (\zeta_{i+1}^{n+\theta,p} - \zeta_i^{n+\theta,p}) \quad (5.78)$$

The second term of [equation \(5.75\)](#)

$$\int_{x_{i-\frac{1}{2}}}^{x_i} g \frac{\partial \zeta^{n+\theta,p}}{\partial x} \theta \Delta h_{i-\frac{1}{4}}^{n+1,p+1} dx + \int_{x_i}^{x_{i+\frac{1}{2}}} g \frac{\partial \zeta^{n+\theta,p}}{\partial x} \theta \Delta h_{i+\frac{1}{4}}^{n+1,p+1} dx \approx \quad (5.79)$$

$$\approx \frac{1}{2} g (\zeta_i^{n+\theta,p} - \zeta_{i-1}^{n+\theta,p}) \theta \Delta h_{i-\frac{1}{4}}^{n+1,p+1} + \frac{1}{2} g (\zeta_{i+1}^{n+\theta,p} - \zeta_i^{n+\theta,p}) \theta \Delta h_{i+\frac{1}{4}}^{n+1,p+1} \quad (5.80)$$

The third term of [equation \(5.75\)](#)

$$\int_{x_{i-\frac{1}{2}}}^{x_i} gh_{i-\frac{1}{4}}^{n+\theta,p} \theta \frac{\partial}{\partial x} (\Delta \zeta^{n+1,p+1}) dx + \int_{x_{i+\frac{1}{2}}}^{x_i} gh_{i+\frac{1}{4}}^{n+\theta,p} \theta \frac{\partial}{\partial x} (\Delta \zeta^{n+1,p+1}) dx = \quad (5.81)$$

$$= \frac{1}{2} gh_{i-\frac{1}{4}}^{n+\theta,p} \theta (\Delta \zeta_i^{n+1,p+1} - \Delta \zeta_{i-1}^{n+1,p+1}) + \frac{1}{2} gh_{i+\frac{1}{4}}^{n+\theta,p} \theta (\Delta \zeta_{i+1}^{n+1,p+1} - \Delta \zeta_i^{n+1,p+1}) \quad (5.82)$$

In a formulation of the shallow-water equations, where the water level is expressed as  $\zeta = h + z_b$ . The equations can be simplified, because

$$\Delta \zeta = \Delta(h + z_b) = \Delta h + \Delta z_b. \quad (5.83)$$

and if  $\Delta z_b = 0$ , i.e. time independent, the contributions to the  $\Delta \zeta$ -equations need to be incorporated in the  $\Delta h$ -equations. Adjusting the matrix coefficients and right-hand side change accordingly.

### 5.3.2.3 Convection

The convection term read:

$$\int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \frac{\partial q^2/h}{\partial x} dx = \frac{q^2}{h} \Big|_{i+\frac{1}{2}}^{n+\theta,p+1} - \frac{q^2}{h} \Big|_{i-\frac{1}{2}}^{n+\theta,p+1} \quad (5.84)$$

The linearization of the convection term around iteration level  $p$  reads:

$$\frac{q^2}{h} \Big|^{n+\theta,p+1} \approx \frac{(q^{n+\theta,p})^2}{h^{n+\theta,p}} + 2 \frac{q^{n+\theta,p}}{h^{n+\theta,p}} \theta \Delta q^{n+1,p+1} - \frac{(q^{n+\theta,p})^2}{(h^{n+\theta,p})^2} \theta \Delta h^{n+1,p+1} \quad (5.85)$$

(where  $\Delta q^{n+\theta,p+1} = \theta \Delta q^{n+1,p+1}$  and  $\Delta h^{n+\theta,p+1} = \theta \Delta h^{n+1,p+1}$ , see [equation \(3.16\)](#)).

### 5.3.2.4 Bed shear stress

The bed shear stress term reads:

$$\int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} c_f \frac{q |q|}{h^2} dx = \int_{x_{i-\frac{1}{2}}}^{x_i} c_f \frac{q |q|}{h^2} dx + \int_{x_i}^{x_{i+\frac{1}{2}}} c_f \frac{q |q|}{h^2} dx \approx \quad (5.86)$$

$$\approx \frac{\Delta x_{i-\frac{1}{2}}}{2} \left( c_{f,i-\frac{1}{4}} \frac{q_{i-\frac{1}{4}} |q_{i-\frac{1}{4}}|}{(h_{i-\frac{1}{4}})^2} \right) + \frac{\Delta x_{i+\frac{1}{2}}}{2} \left( c_{f,i+\frac{1}{4}} \frac{q_{i+\frac{1}{4}} |q_{i+\frac{1}{4}}|}{(h_{i+\frac{1}{4}})^2} \right) \quad (5.87)$$

To avoid the discontinue derivative of the abs-function, this function is replaced by the following  $C^2$ -continue function:

$$|q| = F_{abs}(q) \approx (q^4 + \varepsilon^4)^{1/4}, \quad \varepsilon = 0.01 \quad (5.88)$$

We first linearize the equation and then discretize/integrate in space. The linearization of the bed shear stress term around iteration level  $p$  reads expressed at  $x_{i-\frac{1}{4}}$ :

$$c_{f,i-\frac{1}{4}} F_{abs}(q_{i-\frac{1}{4}}) \frac{q_{i-\frac{1}{4}}}{(h_{i-\frac{1}{4}})^2} \Big|^{n+\theta,p+1} \approx \quad (5.89)$$

$$\begin{aligned} & \approx c_{f,i-\frac{1}{4}} F_{abs}(q_{i-\frac{1}{4}}^{n+\theta,p}) \frac{q_{i-\frac{1}{4}}^{n+\theta,p}}{(h_{i-\frac{1}{4}}^{n+\theta,p})^2} + \\ & + c_{f,i-\frac{1}{4}} \frac{\partial}{\partial q} \left\{ F_{abs}(q_{i-\frac{1}{4}}^{n+\theta,p}) \right\} \frac{q_{i-\frac{1}{4}}^{n+\theta,p}}{(h_{i-\frac{1}{4}}^{n+\theta,p})^2} \theta \Delta q_{i-\frac{1}{4}}^{n+1,p+1} + \\ & + c_{f,i-\frac{1}{4}} F_{abs}(q_{i-\frac{1}{4}}^{n+\theta,p}) \frac{1}{(h_{i-\frac{1}{4}}^{n+\theta,p})^2} \theta \Delta q_{i-\frac{1}{4}}^{n+1,p+1} + \\ & - c_{f,i-\frac{1}{4}} F_{abs}(q_{i-\frac{1}{4}}^{n+\theta,p}) \frac{2q_{i-\frac{1}{4}}^{n+\theta,p}}{(h_{i-\frac{1}{4}}^{n+\theta,p})^3} \theta \Delta h_{i-\frac{1}{4}}^{n+1,p+1} \end{aligned} \quad (5.90)$$

and

$$\frac{\partial}{\partial q} \left\{ F_{abs}(q_{i-\frac{1}{4}}^{n+\theta,p}) \right\} = (q_{i-\frac{1}{4}}^{n+\theta,p})^3 ((q_{i-\frac{1}{4}}^{n+\theta,p})^4 + \varepsilon^4)^{-3/4} \quad (5.91)$$

The integral was split into two parts, both parts are integrated separately. For the left part ( $x_{i-\frac{1}{4}}$ ) we use:

$$c_{f,i-\frac{1}{4}} = \frac{1}{4} (c_{f,i-1} + 3c_{f,i}), \quad (5.92)$$

$$h_{i-\frac{1}{4}}^{n+\theta,p} = \frac{1}{4} (h_{i-1}^{n+\theta,p} + 3h_i^{n+\theta,p}), \quad (5.93)$$

$$q_{i-\frac{1}{4}}^{n+\theta,p} = \frac{1}{4} (q_{i-1}^{n+\theta,p} + 3q_i^{n+\theta,p}), \quad (5.94)$$

and for the right part ( $x_{i+\frac{1}{4}}$ ) we use

$$c_{f,i+\frac{1}{4}} = \frac{1}{4} (3c_{f,i} + c_{f,i+1}), \quad (5.95)$$

$$h_{i+\frac{1}{4}}^{n+\theta,p} = \frac{1}{4} (3h_i^{n+\theta,p} + h_{i+1}^{n+\theta,p}), \quad (5.96)$$

$$q_{i+\frac{1}{4}}^{n+\theta,p} = \frac{1}{4} (3q_i^{n+\theta,p} + q_{i+1}^{n+\theta,p}). \quad (5.97)$$

### 5.3.2.5 Viscosity

The viscosity term read:

$$\int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \frac{\partial}{\partial x} \left( \nu h \frac{\partial(q/h)}{\partial x} \right) dx = \nu \left( \frac{\partial q}{\partial x} - \frac{q}{h} \frac{\partial h}{\partial x} \right) \Big|_{i+\frac{1}{2}} - \nu \left( \frac{\partial q}{\partial x} - \frac{q}{h} \frac{\partial h}{\partial x} \right) \Big|_{i-\frac{1}{2}} \quad (5.98)$$

The linearization of the viscosity term ( $\nu = \text{constant}$ ) around iteration level  $p$  reads (see section E.1 for a derivation):

$$\nu \left( \frac{\partial q_{i+\frac{1}{2}}^{n+\theta,p+1}}{\partial x} - \frac{q_{i+\frac{1}{2}}^{n+\theta,p+1}}{h_{i+\frac{1}{2}}^{n+\theta,p+1}} \frac{\partial h_{i+\frac{1}{2}}^{n+\theta,p+1}}{\partial x} \right) \approx \quad (5.99)$$

$$\begin{aligned} & \approx \nu \frac{\partial q_{i+\frac{1}{2}}^{n+\theta,p}}{\partial x} - \nu \frac{q_{i+\frac{1}{2}}^{n+\theta,p}}{h_{i+\frac{1}{2}}^{n+\theta,p}} \frac{\partial h_{i+\frac{1}{2}}^{n+\theta,p}}{\partial x} + \\ & + \underbrace{\nu \theta \frac{\partial}{\partial x} (\Delta q_{i+\frac{1}{2}}^{n+1,p+1})}_{\mathcal{A}} - \underbrace{\nu \frac{1}{h_{i+\frac{1}{2}}^{n+\theta,p}} \frac{\partial h_{i+\frac{1}{2}}^{n+\theta,p}}{\partial x} \theta \Delta q_{i+\frac{1}{2}}^{n+1,p+1}}_{\mathcal{B}} + \\ & + \underbrace{\nu \frac{q_{i+\frac{1}{2}}^{n+\theta,p}}{(h_{i+\frac{1}{2}}^{n+\theta,p})^2} \frac{\partial h_{i+\frac{1}{2}}^{n+\theta,p}}{\partial x} \theta \Delta h_{i+\frac{1}{2}}^{n+1,p+1}}_{\mathcal{C}} - \underbrace{\nu \frac{q_{i+\frac{1}{2}}^{n+\theta,p}}{h_{i+\frac{1}{2}}^{n+\theta,p}} \theta \frac{\partial}{\partial x} (\Delta h_{i+\frac{1}{2}}^{n+1,p+1})}_{\mathcal{D}} \end{aligned} \quad (5.100)$$

where  $\mathcal{A}$ ,  $\mathcal{B}$ ,  $\mathcal{C}$  and  $\mathcal{D}$  multiplied by  $\theta$  are coefficients in the matrix of the  $\Delta$ -formulation. For the part at  $x_{i-\frac{1}{2}}$  a similar expression is feasible.

### 5.3.3 Discretizations at boundary

For the 1D linear wave equations (equation (5.1)) at each boundary one boundary condition need to be prescribed, that is the ingoing wave, called **essential** boundary condition (Dirichlet or Neumann condition). And one boundary condition to handle the outgoing wave, called **natural** boundary condition.

The boundary conditions are presented for the left/west boundary. First the **natural** boundary is discussed and after that the **essential** boundary condition. A similar derivation can be given for right/east boundary.

The **essential** boundary condition is to be assumed somewhere in the first control volume, ( $x_{i_{bc}}$  with  $i_{bc} \in [i - \frac{1}{2}, i + \frac{1}{2}]$ ). For simplicity the boundary condition is chosen to be on node  $i = 1$  (location  $x_1$ ).

### 5.3.3.1 Essential boundary condition

The **essential** boundary condition is to be assumed somewhere in the first control volume, ( $x_{i_{bc}}$  with  $i_{bc} \in [i - \frac{1}{2}, i + \frac{1}{2}]$ ). For simplicity the boundary condition is chosen to be on node  $i = 1$  (location  $x_1$ ).

The **essential** boundary condition for the left/west boundary at  $x_1$  reads, describing the ingoing wave (indicated with  $h^+$ ,  $q^+$ ) with as less as possible disturbing the outgoing wave ([equation \(5.59\)](#)):

$$\left( \sqrt{gh} - \frac{q}{h} \right) \frac{\partial h^+}{\partial t} + \frac{\partial q^+}{\partial t} = F(t) \quad (5.101)$$

$$\left( \sqrt{gh} + \frac{q}{h} \right) \frac{\partial h^+}{\partial t} - \frac{\partial q^+}{\partial t} = 0 \quad (5.102)$$

[Equation \(5.102\)](#) means that the ingoing wave does not disturb the outgoing wave.

The essential boundary condition for the right/east boundary at  $x_{I+\frac{1}{2}}$  reads, describing the ingoing wave (indicated with  $h^-$ ,  $q^-$ ) with as less as possible disturbing the outgoing wave ([equation \(5.59\)](#)):

$$\left( \sqrt{gh} + \frac{q}{h} \right) \frac{\partial h^-}{\partial t} - \frac{\partial q^-}{\partial t} = G(t) \quad (5.103)$$

$$\left( \sqrt{gh} - \frac{q}{h} \right) \frac{\partial h^-}{\partial t} + \frac{\partial q^-}{\partial t} = 0 \quad (5.104)$$

[Equation \(5.104\)](#) means that the ingoing wave does not disturb the outgoing wave.

#### *Given water level at left / west boundary*

Adding the equations ((5.101) + (5.102)) yields

$$2\sqrt{gh} \frac{\partial h}{\partial t} = F(t) \quad (5.105)$$

So the essential boundary condition for incoming signal (if  $\partial z_b / \partial t = 0$ ) reads

$$\left( \sqrt{gh} - \frac{q}{h} \right) \frac{\partial h^+}{\partial t} + \frac{\partial q^+}{\partial t} = 2\sqrt{gh} \frac{\partial \zeta_{given}}{\partial t} + \varepsilon(\zeta_{given} - \zeta) \quad (5.106)$$

a correction term is added, to prevent drifting away of the solution (an integration constant is missing). The variable  $\varepsilon$  has dimension [ $\text{m s}^{-2}$ ].

The discretization of boundary [equation \(7.112\)](#) at  $x = i + \frac{1}{2}$  reads

$$\begin{aligned} & \left( \sqrt{gh^{n+\theta,p+1}} - \frac{q^{n+\theta,p+1}}{h^{n+\theta,p+1}} \right) \frac{\partial h^+}{\partial t} + \frac{\partial q^+}{\partial t} = \\ & = 2\sqrt{gh^{n+\theta,p+1}} \frac{\partial \zeta_{given}}{\partial t} + \varepsilon((\zeta_{given} - z_b) - h^{n+\theta,p}) \end{aligned} \quad (5.107)$$

*Given water flux at left/west boundary*

Subtracting the equations ((5.101) – (5.102)), yields:

$$-2\frac{q}{h}\frac{\partial h}{\partial t} + 2\frac{\partial q}{\partial t} = F(h, q, t) \quad (5.108)$$

So the essential boundary condition for incoming signal reads

$$\left(\sqrt{gh} - \frac{q}{h}\right)\frac{\partial h^+}{\partial t} + \frac{\partial q^+}{\partial t} = -2\frac{q}{h}\frac{\partial h}{\partial t} + 2\frac{\partial q}{\partial t} \quad (5.109)$$

Using [equation \(5.102\)](#) (ingoing information does not disturb outgoing information)

$$\left(\sqrt{gh} + \frac{q}{h}\right)\frac{\partial h^+}{\partial t} - \frac{\partial q^+}{\partial t} = 0 \Rightarrow \frac{\partial h^+}{\partial t} = \frac{1}{\sqrt{gh} + \frac{q}{h}}\frac{\partial q^+}{\partial t} \quad (5.110)$$

substituting [equation \(5.110\)](#) into the right hand side of [equation \(5.109\)](#), yields

$$\boxed{\left(\sqrt{gh} - \frac{q}{h}\right)\frac{\partial h^+}{\partial t} + \frac{\partial q^+}{\partial t} = 2\left(\frac{\sqrt{gh}}{\sqrt{gh} + \frac{q}{h}}\right)\frac{\partial q_{given}}{\partial t} + \varepsilon(q_{given} - q)} \quad (5.111)$$

a correction term is added, to prevent drifting away of the solution (an integration constant is missing). The variable  $\varepsilon$  has dimension [s<sup>-1</sup>]. The discretization of boundary [equation \(5.111\)](#) at  $x = i + \frac{1}{2}$  reads

$$\begin{aligned} & \left(\sqrt{gh^{n+\theta,p+1}} - \frac{q^{n+\theta,p+1}}{h^{n+\theta,p+1}}\right)\frac{\partial h}{\partial t} + \frac{\partial q}{\partial t} = \\ & = 2\left(\frac{\sqrt{gh^{n+\theta,p+1}}}{\sqrt{gh^{n+\theta,p+1}} + \frac{q^{n+\theta,p+1}}{h^{n+\theta,p+1}}}\right)\frac{\partial q_{given}}{\partial t} + \varepsilon(q_{given} - q^{n+\theta,p}) \end{aligned} \quad (5.112)$$

### 5.3.3.2 Natural boundary condition

The **natural** boundary condition for the left/west boundary, describing the undisturbed outgoing wave, reads ([equation \(5.59\)](#)):

$$-\left(\sqrt{gh} + \frac{q}{h}\right)\underbrace{\left(\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} + \dots\right)}_{\text{continuity eq.}} + \underbrace{\left(\frac{\partial q}{\partial t} + gh\frac{\partial \zeta}{\partial x} + \dots\right)}_{\text{momentum eq.}} = 0 \quad (5.113)$$

For the **natural** boundary the values at the boundary ( $x_{i+\frac{1}{2}}$  with  $i = 0$ ) of  $h$  and  $q$  are computed as follows:

$$\begin{aligned} h_{i+\frac{1}{2}} &= \frac{1}{2}(h_i + h_{i+1}) + \frac{\alpha_{bnd}}{2}(h_i - 2h_{i+1} + h_{i+2}) \\ &= \frac{1}{2}(1 + \alpha_{bnd})h_i + \frac{1}{2}(1 - 2\alpha_{bnd})h_{i+1} + \frac{1}{2}\alpha_{bnd}h_{i+2} \end{aligned} \quad (5.114)$$

$$\begin{aligned} q_{i+\frac{1}{2}} &= \frac{1}{2}(q_i + q_{i+1}) + \frac{\alpha_{bnd}}{2}(q_i - 2q_{i+1} + q_{i+2}) \\ &= \frac{1}{2}(1 + \alpha_{bnd})q_i + \frac{1}{2}(1 - 2\alpha_{bnd})q_{i+1} + \frac{1}{2}\alpha_{bnd}q_{i+2} \end{aligned} \quad (5.115)$$

with  $\alpha_{bnd} = 2\alpha - \frac{1}{2} = -\frac{1}{4}$ , see [Borsboom \(2009\)](#).

### Time derivative, continuity equation

At the left/west boundary ( $x_{i+\frac{1}{2}}$  with  $i = 0$ ) the time discretization of the continuity equation for the **natural** boundary condition, describing the outgoing wave, reads:

$$\frac{\partial h}{\partial t} \approx \frac{1}{\Delta t} \left( h_{i+\frac{1}{2}}^{n+1} - h_{i+\frac{1}{2}}^n \right) \quad (5.116)$$

A diffusion like term is added to the boundary equation to damp the reflection of spurious waves. A coefficient  $\alpha_{bnd}$  is placed before that extra term, the optimal value of this coefficient is taken from the analysis in [Borsboom \(2009\)](#).

$$\begin{aligned} \frac{1}{\Delta t} & \left( \frac{1}{2} (h_i^{n+1,p+1} + h_{i+1}^{n+1,p+1}) + \frac{\alpha_{bnd}}{2} (h_i^{n+1,p+1} - 2h_{i+1}^{n+1,p+1} + h_{i+2}^{n+1,p+1}) + \right. \\ & \left. - \left( \frac{1}{2} (h_i^n + h_{i+1}^n) + \frac{\alpha_{bnd}}{2} (h_i^n - 2h_{i+1}^n + h_{i+2}^n) \right) \right) \end{aligned} \quad (5.117)$$

After rearranging the equation into an implicit and an explicit part it reads:

$$\begin{aligned} \frac{1}{\Delta t} & \left( \frac{1}{2} (\Delta h_i^{n+1,p+1} + \Delta h_{i+1}^{n+1,p+1}) + \right. \\ & + \frac{\alpha_{bnd}}{2} (\Delta h_i^{n+1,p+1} - 2\Delta h_{i+1}^{n+1,p+1} + \Delta h_{i+2}^{n+1,p+1}) \Big) + \\ & + \frac{1}{\Delta t} \left\{ \frac{1}{2} (h_i^{n+1,p} + h_{i+1}^{n+1,p}) + \frac{\alpha_{bnd}}{2} (h_i^{n+1,p} - 2h_{i+1}^{n+1,p} + h_{i+2}^{n+1,p}) + \right. \\ & \left. - \left( \frac{1}{2} (h_i^n + h_{i+1}^n) + \frac{\alpha_{bnd}}{2} (h_i^n - 2h_{i+1}^n + h_{i+2}^n) \right) \right\} \end{aligned} \quad (5.118)$$

### Mass flux, continuity equation

At the left/west boundary ( $x_{i+\frac{1}{2}}$  with  $i = 0$ ) the discretization of the mass flux for the **natural** boundary condition, describing the outgoing wave, reads:

$$\frac{\partial q}{\partial x} \approx \frac{1}{\Delta x} (q_{i+1}^{n+\theta,p+1} - q_i^{n+\theta,p+1}) \quad (5.119)$$

which will be approximated by

$$\frac{1}{\Delta x} \left( (q_{i+1}^{n+\theta,p} + \theta \Delta q_{i+1}^{n+1,p+1}) - (q_i^{n+\theta,p+1} + \theta \Delta q_i^{n+1,p+1}) \right) \quad (5.120)$$

$\Leftrightarrow$

$$\frac{1}{\Delta x} (\theta \Delta q_{i+1}^{n+1,p+1} - \theta \Delta q_i^{n+1,p+1}) + \frac{1}{\Delta x} \left\{ q_{i+1}^{n+\theta,p} - q_i^{n+\theta,p+1} \right\} \quad (5.121)$$

### Time derivative, momentum equation

At the left/west boundary ( $x_{i+\frac{1}{2}}$  with  $i = 0$ ) the time discretization of the momentum equation for the **natural** boundary condition, describing the outgoing wave, reads:

$$\frac{\partial q}{\partial t} \approx \frac{1}{\Delta t} (q_{i+\frac{1}{2}}^{n+1} - q_{i+\frac{1}{2}}^n) \quad (5.122)$$

A diffusion like term is added to the boundary equation to damp the reflection of spurious waves. A coefficient  $\alpha_{bnd}$  is placed before that extra term, the optimal value of this coefficient is taken from the analysis in [Borsboom \(2009\)](#).

$$\frac{1}{\Delta t} \left( \frac{1}{2} (q_i^{n+1,p+1} + q_{i+1}^{n+1,p+1}) + \frac{\alpha_{bnd}}{2} (q_i^{n+1,p+1} - 2q_{i+1}^{n+1,p+1} + q_{i+2}^{n+1,p+1}) + \right. \\ \left. - \left( \frac{1}{2} (q_i^n + q_{i+1}^n) + \frac{\alpha_{bnd}}{2} (q_i^n - 2q_{i+1}^n + q_{i+2}^n) \right) \right) \quad (5.123)$$

After rearranging the equation into an implicit and an explicit part it reads:

$$\frac{1}{\Delta t} \left( \frac{1}{2} (\Delta q_i^{n+1,p+1} + \Delta q_{i+1}^{n+1,p+1}) + \right. \\ \left. + \frac{\alpha_{bnd}}{2} (\Delta q_i^{n+1,p+1} - 2\Delta q_{i+1}^{n+1,p+1} + \Delta q_{i+2}^{n+1,p+1}) \right) + \\ + \frac{1}{\Delta t} \left\{ \frac{1}{2} (q_i^{n+1,p} + q_{i+1}^{n+1,p}) + \frac{\alpha_{bnd}}{2} (q_i^{n+1,p} - 2q_{i+1}^{n+1,p} + q_{i+2}^{n+1,p}) + \right. \\ \left. - \frac{1}{2} (q_i^n + q_{i+1}^n) - \frac{\alpha_{bnd}}{2} (q_i^n - 2q_{i+1}^n + q_{i+2}^n) \right\} \quad (5.124)$$

### *Pressure term, momentum equation*

At the left/west boundary ( $x_{i+\frac{1}{2}}$  with  $i = 0$ ) the discretization of the pressure term for the **natural** boundary condition, describing the outgoing wave, reads:

$$gh \frac{\partial \zeta}{\partial x} \approx gh_{i+\frac{1}{2}}^{n+\theta,p+1} \frac{\partial}{\partial x} (\zeta_{i+\frac{1}{2}}^{n+\theta,p+1}) \quad (5.125)$$

In a formulation of the shallow-water equations, where the equation for the free-surface level  $\zeta$  reduces to  $\zeta = h + z_b$  (excluding drying and flooding), the equations can be simplified, because  $\Delta\zeta = \Delta h$  (when  $z_b$  is not time dependent). In this case, the contributions to the  $\Delta\zeta$ -equations need to be incorporated in the  $\Delta h$ -equations. The pressure term will then be approximated by

$$\frac{1}{\Delta x} gh_{i+\frac{1}{2}}^{n+\theta,p} (\zeta_{i+1}^{n+\theta,p} - \zeta_i^{n+\theta,p}) + \\ + \frac{1}{\Delta x} g (\zeta_{i+1}^{n+\theta,p} - \zeta_i^{n+\theta,p}) \theta \Delta h_{i+\frac{1}{2}}^{n+1,p+1} + \\ + \frac{1}{\Delta x} gh_{i+\frac{1}{2}}^{n+\theta,p} \theta (\Delta \zeta_{i+1}^{n+1,p+1} - \Delta \zeta_i^{n+1,p+1}) \quad (5.126)$$

After rearranging the equation into an implicit and an explicit part it reads:

$$\frac{1}{\Delta x} g (\zeta_{i+1}^{n+\theta,p} - \zeta_i^{n+\theta,p}) \theta \Delta h_{i+\frac{1}{2}}^{n+1,p+1} + \frac{1}{\Delta x} gh_{i+\frac{1}{2}}^{n+\theta,p} \theta (\Delta \zeta_{i+1}^{n+1,p+1} - \Delta \zeta_i^{n+1,p+1}) + \\ + \left\{ \frac{1}{\Delta x} gh_{i+\frac{1}{2}}^{n+\theta,p} (\zeta_{i+1}^{n+\theta,p} - \zeta_i^{n+\theta,p}) \right\} \quad (5.127)$$

### Convection term, momentum equation

At the left/west boundary ( $x_{i+\frac{1}{2}}$  with  $i = 0$ ) the discretization of the convection term for the **natural** boundary condition, describing the outgoing wave, reads:

$$\frac{\partial q^2/h}{\partial x} = \frac{2q}{h} \frac{\partial q}{\partial x} - \frac{q^2}{h^2} \frac{\partial h}{\partial x} \quad (5.128)$$

which will be approximated by

$$\begin{aligned} & \left( \frac{2q}{h} \frac{\partial q}{\partial x} - \frac{q^2}{h^2} \frac{\partial h}{\partial x} \right) \Big|_{i+\frac{1}{2}}^{n+\theta,p+1} \approx \\ & \approx \underbrace{\frac{2q_{i+\frac{1}{2}}^{n+\theta,p}}{h_{i+\frac{1}{2}}^{n+\theta,p}} \frac{\partial}{\partial x} (q_{i+\frac{1}{2}}^{n+\theta,p}) - \frac{(q_{i+\frac{1}{2}}^{n+\theta,p})^2}{(h_{i+\frac{1}{2}}^{n+\theta,p})^2} \frac{\partial}{\partial x} (h_{i+\frac{1}{2}}^{n+\theta,p})}_{\text{to right hand side}} + \\ & + \underbrace{\left( -\frac{2q_{i+\frac{1}{2}}^{n+\theta,p}}{(h_{i+\frac{1}{2}}^{n+\theta,p})^2} \frac{\partial}{\partial x} (q_{i+\frac{1}{2}}^{n+\theta,p}) + \frac{2(q_{i+\frac{1}{2}}^{n+\theta,p})^2}{(h_{i+\frac{1}{2}}^{n+\theta,p})^3} \frac{\partial}{\partial x} (h_{i+\frac{1}{2}}^{n+\theta,p}) \right) \theta \Delta h_{i+\frac{1}{2}}^{n+1,p+1}}_{\mathcal{A}} + \\ & + \underbrace{\left( \frac{2}{h_{i+\frac{1}{2}}^{n+\theta,p}} \frac{\partial}{\partial x} (q_{i+\frac{1}{2}}^{n+\theta,p}) - \frac{2q_{i+\frac{1}{2}}^{n+\theta,p}}{(h_{i+\frac{1}{2}}^{n+\theta,p})^2} \frac{\partial}{\partial x} (h_{i+\frac{1}{2}}^{n+\theta,p}) \right) \theta \Delta q_{i+\frac{1}{2}}^{n+1,p+1}}_{\mathcal{B}} + \\ & + \underbrace{\left( -\frac{(q_{i+\frac{1}{2}}^{n+\theta,p})^2}{(h_{i+\frac{1}{2}}^{n+\theta,p})^2} \right) \theta \frac{\partial}{\partial x} (\Delta h_{i+\frac{1}{2}}^{n+1,p+1}) + \frac{2q_{i+\frac{1}{2}}^{n+\theta,p}}{h_{i+\frac{1}{2}}^{n+\theta,p}} \theta \frac{\partial}{\partial x} (\Delta q_{i+\frac{1}{2}}^{n+1,p+1})}_{\mathcal{D}} \end{aligned} \quad (5.129)$$

(5.130)

where  $\mathcal{A}$ ,  $\mathcal{B}$ ,  $\mathcal{C}$  and  $\mathcal{D}$  multiplied by  $\theta$  are the coefficients in the matrix of the  $\Delta$ -formulation.

### Bed shear stress term, momentum equation

At the left/west boundary ( $x_{i+\frac{1}{2}}$  with  $i = 0$ ) the discretization of the bed shear stress term for the **natural** boundary condition, describing the outgoing wave, reads:

$$c_f \frac{q |q|}{h^2} \approx c_{f,i+\frac{1}{2}} \frac{q_{i+\frac{1}{2}}^{n+\theta,p+1} |q_{i+\frac{1}{2}}^{n+\theta,p+1}|}{(h_{i+\frac{1}{2}}^{n+\theta,p+1})^2} \quad (5.131)$$

To avoid the discontinuous derivative of the abs-function, this function is replaced by a  $C^2$ -continuous function (equation (5.88))

$$|q| \approx F_{abs}(q) = (q^4 + \varepsilon^4)^{1/4}, \quad \varepsilon = 0.01 \quad (5.132)$$

which will be approximated by

$$\begin{aligned}
& c_{f,i+\frac{1}{2}} \frac{q_{i+\frac{1}{2}}^{n+\theta,p} F_{abs}(q_{i+\frac{1}{2}}^{n+\theta,p})}{(h_{i+\frac{1}{2}}^{n+\theta,p})^2} + \\
& + c_{f,i+\frac{1}{2}} \frac{F_{abs}(q_{i+\frac{1}{2}}^{n+\theta,p})}{(h_{i+\frac{1}{2}}^{n+\theta,p})^2} \theta \Delta q_{i+\frac{1}{2}}^{n+1,p+1} + \\
& + c_{f,i+\frac{1}{2}} \frac{q_{i+\frac{1}{2}}^{n+\theta,p}}{(h_{i+\frac{1}{2}}^{n+\theta,p})^2} \frac{\partial}{\partial q} \left( F_{abs}(q_{i+\frac{1}{2}}^{n+\theta,p}) \right) \theta \Delta q_{i+\frac{1}{2}}^{n+1,p+1} + \\
& - c_{f,i+\frac{1}{2}} \frac{2q_{i+\frac{1}{2}}^{n+\theta,p} F_{abs}(q_{i+\frac{1}{2}}^{n+\theta,p})}{(h_{i+\frac{1}{2}}^{n+\theta,p})^3} \theta \Delta h_{i+\frac{1}{2}}^{n+1,p+1}
\end{aligned} \tag{5.133}$$

with

$$\frac{\partial}{\partial q} \left( F_{abs}(q_{i+\frac{1}{2}}^{n+\theta,p}) \right) = (q_{i+\frac{1}{2}}^{n+\theta,p})^3 ((q_{i+\frac{1}{2}}^{n+\theta,p})^4 + \varepsilon^4)^{-3/4} \tag{5.134}$$

### Viscosity term, momentum equation

At the left/west boundary ( $x_{i+\frac{1}{2}}$  with  $i = 0$ ) the discretization of the viscosity term for the **natural** boundary condition, describing the outgoing wave, reads:

#### Remark:

- Strictly spoken there is no separation between left and right going waves when there is a viscosity term.

$$\frac{\partial}{\partial x} \left( \nu h \frac{\partial(q/h)}{\partial x} \right) = \tag{5.135}$$

$$\begin{aligned}
& = \frac{\partial \nu}{\partial x} \left( \frac{\partial q}{\partial x} - \frac{q}{h} \frac{\partial h}{\partial x} \right) + \nu \frac{\partial h}{\partial x} \left( \frac{1}{h} \frac{\partial q}{\partial x} - \frac{q}{h^2} \frac{\partial h}{\partial x} \right) + \\
& - \nu \frac{1}{h} \frac{\partial q}{\partial x} \frac{\partial h}{\partial x} + \nu \frac{\partial^2 q}{\partial x^2} - \nu \frac{1}{h} \frac{\partial h}{\partial x} \frac{\partial q}{\partial x} - \nu \frac{2q}{h^2} \frac{\partial h}{\partial x} \frac{\partial h}{\partial x} + \nu \frac{q}{h} \frac{\partial^2 h}{\partial x^2}
\end{aligned} \tag{5.136}$$

which will be approximated by the following discretizations:

$$\frac{\partial \nu}{\partial x} \approx \frac{\nu_{i+1} - \nu_i}{\Delta x} \tag{5.137}$$

$$\frac{\partial q}{\partial x} \approx \frac{q_{i+1}^{n+\theta,p+1} - q_i^{n+\theta,p+1}}{\Delta x} \tag{5.138}$$

$$\frac{\partial h}{\partial x} \approx \frac{h_{i+1}^{n+\theta,p+1} - h_i^{n+\theta,p+1}}{\Delta x} \tag{5.139}$$

$$\frac{\partial^2 q}{\partial x^2} \approx \frac{q_{i-1}^{n+\theta,p+1} - 2q_i^{n+\theta,p+1} + q_{i+1}^{n+\theta,p+1}}{\Delta x} \tag{5.140}$$

$$\frac{\partial^2 h}{\partial x^2} \approx \frac{h_{i-1}^{n+\theta,p+1} - 2h_i^{n+\theta,p+1} + h_{i+1}^{n+\theta,p+1}}{\Delta x} \tag{5.141}$$

**TODO 5.2:** Natural boundary: viscosity term

**TODO**

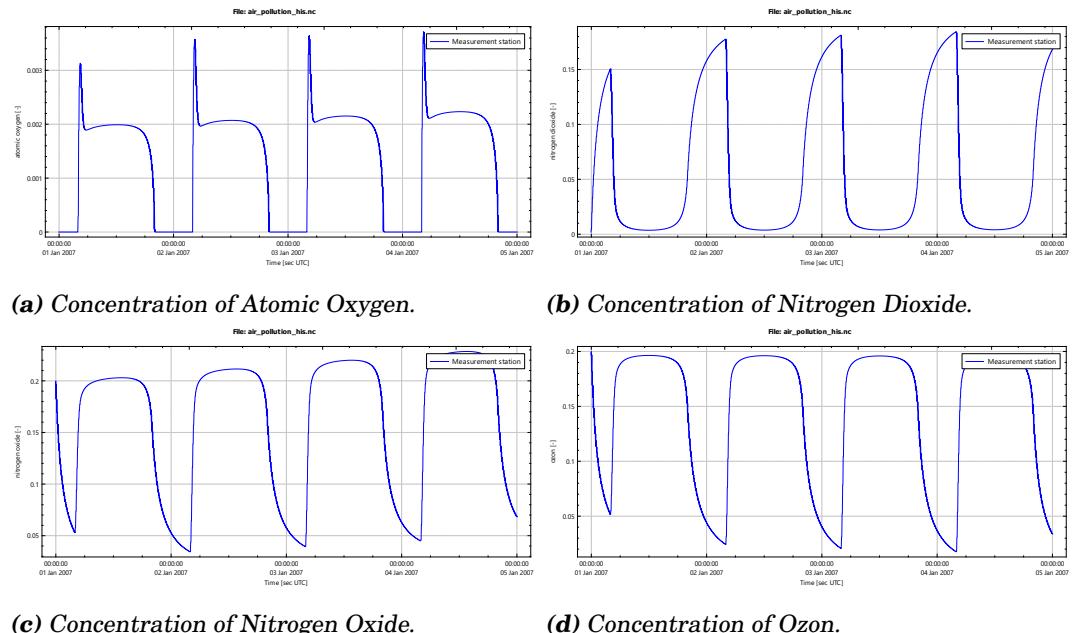
# 6 Numerical experiments

## 6.1 0-D, sources and sinks

In this section the numerical results are given for the 0-dimensional air pollution example as described in [section 5.1.1](#) and for the Brusselator, as described in [section 5.1.2](#).

### 6.1.1 Air pollution

Some numerical results of the air pollution example ([section 5.1.1](#)) is:



**Figure 6.1:** Result plots of the different constituents, compute with the fully implicit time integration method with a time step of 0.5 [s].

### Different time integrators

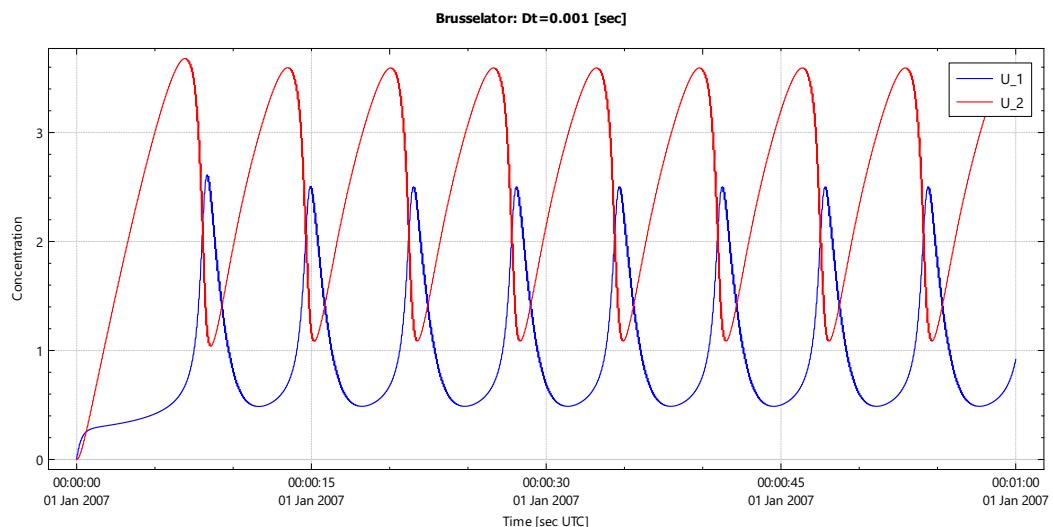
Numerical stability for different values of  $\Delta t$  are studied for Euler-explicit, Runge-Kutta-4 and the fully implicit  $\Delta$ -formulation.

**Table 6.1:** Stability for different time integrators

	Time step [s]	Euler explicit	Runge-Kutta 4	Fully Implicit $\Delta$ -formulation
<b>1</b>	0.5	-	✓	✓
<b>2</b>	60	✓	✓	✓
<b>3</b>	120	Unstable	✓	✓
<b>4</b>	180	-	Unstable	✓
<b>5</b>	240	-	-	✓
<b>6</b>	300	-	-	✓
<b>7</b>	900	-	-	✓
<b>8</b>	1800	-	-	✓
<b>9</b>	3600	-	-	✓

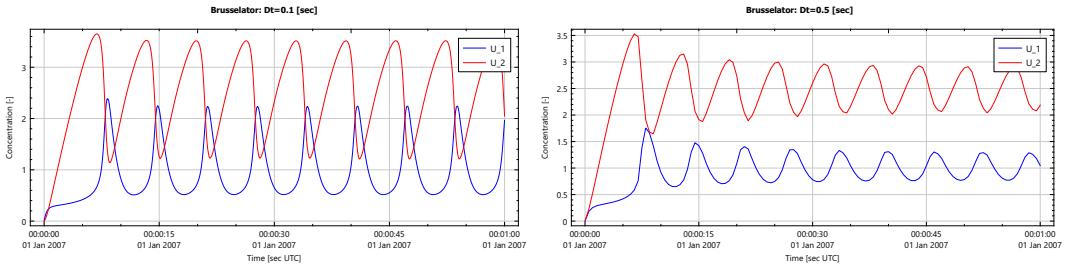
### 6.1.2 Brusselator

Some numerical results of the brusselator example (section 5.1.2) is:



**Figure 6.2:** Fully Implicit:  $\Delta t = 0.001$  [s],  $k_1 = 1$ ,  $k_2 = 2.5$ .

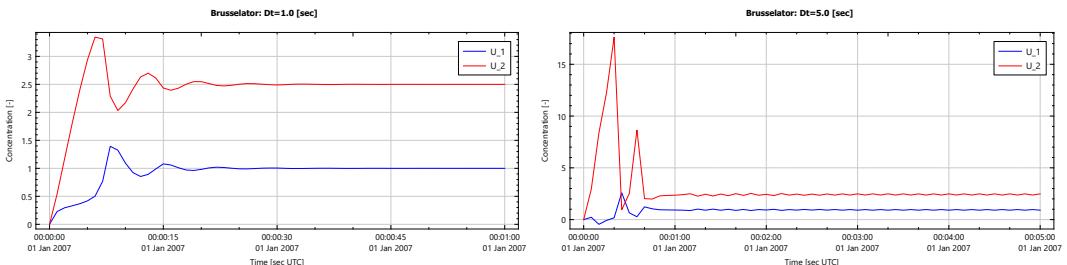
The solution presented in Figure 6.2 is assumed to be the reference (analytic) solution of equation (5.32).



(a) Fully Implicit:  $\Delta t = 0.1$  [s],  $k_1 = 1$ ,  $k_2 = 2.5$  (b) Fully Implicit:  $\Delta t = 0.5$  [s],  $k_1 = 1$ ,  $k_2 = 2.5$

**Figure 6.3:** Result plots for constant value of  $k_1 = 1$  and  $k_2 = 2.5$ , computed with a fully implicit ( $\Delta$  formulation) time integration method for different time steps  $\Delta t = 0.1, 0.5$  [s].

Extra attention is needed for the Fully Implicit time integration with larger time step:



(a) Fully Implicit:  $\Delta t = 1.0$  [s],  $k_1 = 1$ ,  $k_2 = 2.5$  (b) Fully Implicit:  $\Delta t = 5.0$  [s],  $k_1 = 1$ ,  $k_2 = 2.5$

**Figure 6.4:** Result plots for constant value of  $k_1 = 1$  and  $k_2 = 2.5$ , computed with a fully implicit ( $\Delta$  formulation) time integration method for different time steps  $\Delta t = 1.0, 5.0$  [s].

Figure 6.4a converge to the equilibrium state  $(u_1, u_2) = (1.0, 2.5)$  and Figure 6.4b looks to converge to the equilibrium state  $(u_1, u_2) = (1.0, 2.5)$  but is still wiggling after 5 [min] of simulation time (even after one day — not presented here). How these equations are discretized is given in equation (5.1.2).

### Different time integrators

Numerical stability for different values of  $\Delta t$  are studied for the Runge-Kutta-4 and fully implicit  $\Delta$ -formulation.

**Table 6.2:** Stability of different time integrators for the Brusselator.

Time step [s]	Runge-Kutta 4	Fully Implicit $\Delta$ -formulation
1 0.1	✓	✓

	Time step [s]	Runge-Kutta 4	Fully Implicit $\Delta$ -formulation
<b>2</b>	0.2	✓	✓
<b>3</b>	0.5	✓	✓
<b>4</b>	1.0	Unstable	✓
<b>5</b>	2.0		✓
<b>6</b>	5.0		✓

## 6.2 1-D Advection equation

The considered advection equation reads:

$$\frac{\partial c}{\partial t} + \frac{\partial uc}{\partial x} = 0, \quad (6.1)$$

With a velocity of  $u = 10 \text{ [m s}^{-1}\text{]}$ , which coincide with the wave celerity of the 1D-wave numerical experiments as described in section 6.4.1.

$$u(x, t) = 10 \text{ [m s}^{-1}\text{]} \quad (6.2)$$

and with a prescribed boundary condition at the left side of the domain

$$c(0, t) = f_c(t). \quad (6.3)$$

### 6.2.1 Transport of a constant constituent at the boundary

The prescribed boundary condition for the constituent reads

$$c(0, t) = c_{given} \begin{cases} \frac{1}{2} \left( \cos \left( \pi \frac{t_{reg}-t}{t_{reg}} \right) + 1 \right) & \text{if } t < t_{reg}, \\ 1 & \text{if } t \geq t_{reg}, \end{cases} \quad (6.4)$$

where

$t_{reg}$  The regularization time for the given time-series, [s]

#### Numerical experiment

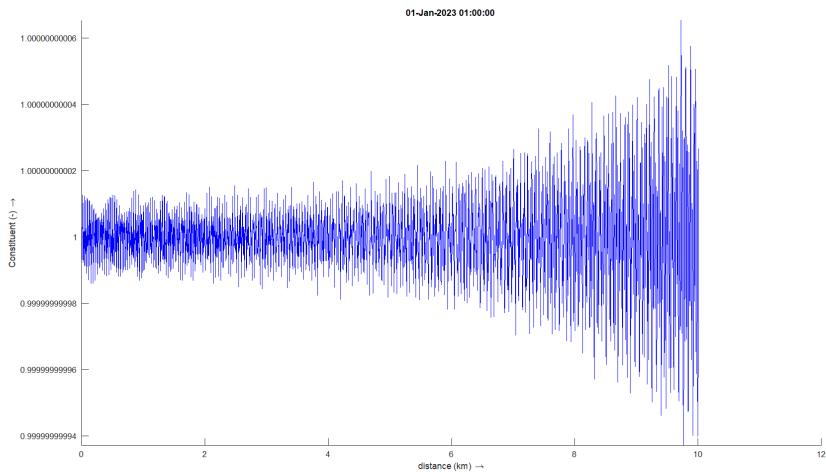
The numerical experiment is performed with the following parameters:

- Length of the domain,  $L_x = 12\,000 \text{ [m]}$
- Grid size,  $\Delta x = 10 \text{ [m]}$
- Start time,  $t_{start} = 0 \text{ [s]}$
- End time,  $t_{stop} = 3600 \text{ [s]}$
- Timestep,  $\Delta t = 5 \text{ [s]}$
- Regularization time for time-series,  $t_{reg} = 600 \text{ [s]}$
- Prescribed constant velocity,  $u_{given}(x, t) = 10 \text{ [m s}^{-1}\text{]}$

- Prescribed initial value of the constituent,  $c(x, 0) = 0$  [–].
- Prescribed constituent on boundary at  $x = 0$  is given by [equation \(6.4\)](#).
- No boundary is prescribed at  $x = 12\,000$  [m].

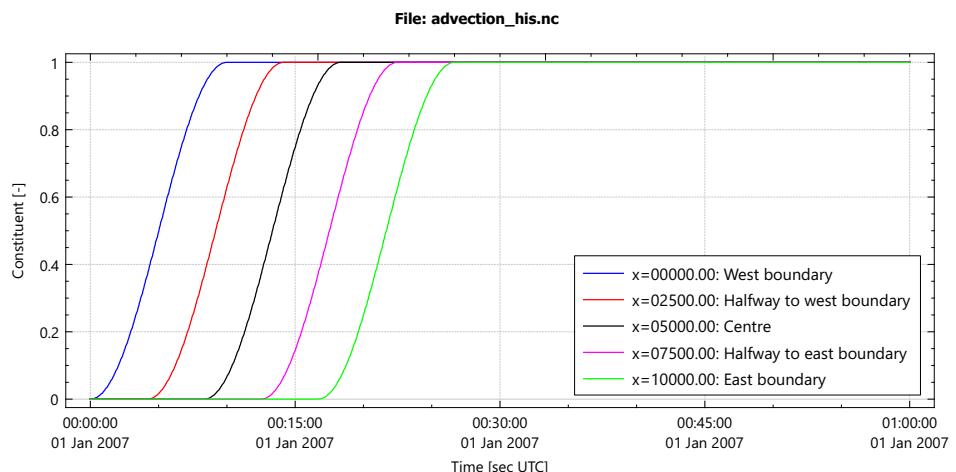
### *Results of the numerical experiments*

A map picture at  $t = 3600$  [s] and time-series are given for this experiment. As seen from the map figure there are very small spurious waves traveling from right to left. These spurious waves are fully generated by the numerical scheme at the right boundary, because the continuous advection equation does **not** allow information traveling from right to left.



**Figure 6.5:** Spurious waves at  $t = 3600$  [s]. Range from  $1 \pm 8 \times 10^{-9}$ .

Results for several observation stations along the channel are shown in [Figure 6.6](#)



**Figure 6.6:** Time-series for several stations in the model, showing the transition behavior between the initial situation and the time-independent solution.

## 6.2.2 Transport of a time-dependent constituent at the boundary

The prescribed boundary condition for the constituent reads

$$c(0, t) = c_{given} \begin{cases} \frac{1}{2} \left( \cos \left( \pi \frac{t_{reg}-t}{t_{reg}} \right) + 1 \right) & \text{if } t < t_{reg}, \\ -\cos \left( \pi \frac{t}{t_{reg}} \right) & \text{if } t \geq t_{reg}, \end{cases} \quad (6.5)$$

where

$t_{reg}$  The regularization time for the given time-series, [s]

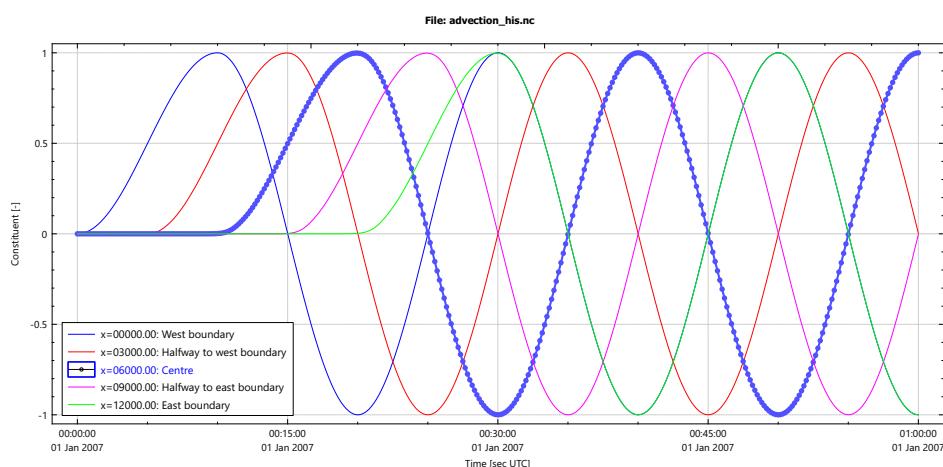
### Numerical experiment

The numerical experiment is performed with the following parameters:

- Length of the domain, 12 000 [m]
- Grid size,  $\Delta x = 10$  [m]
- Start time,  $t_{start} = 0$  [s]
- End time,  $t_{stop} = 3600$  [s]
- Timestep,  $\Delta t = 10$  [s]
- Regularization time for time-series,  $t_{reg} = 600$  [s]
- Prescribed constant velocity,  $u_{given}(x, t) = 10$  [ $\text{m s}^{-1}$ ]
- Prescribed initial value of the constituent,  $c(x, 0) = 0$  [-].
- Prescribed constituent on boundary at  $x = 0$  is given by equation (6.4).
- No boundary is prescribed at  $x = 12 000$  [m].

### Results of the numerical experiments

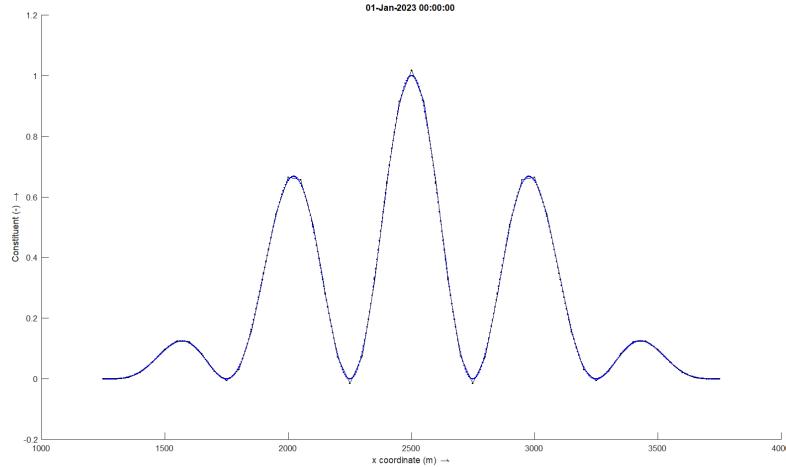
Results for several observation stations along the channel are shown in Figure 6.7:



**Figure 6.7:** Time-series for several stations in the model, showing the transition behavior between the initial situation and the time-independent solution.

### 6.2.3 Transport of a wave package inside the domain

The initial condition are computed as described in [section 4.5](#) and is illustrated in [Figure 6.8](#):



**Figure 6.8:** Compatible initial condition of the wave package. Blue: Initial condition when  $\Delta x = 5$  [m], Black: Initial condition when  $\Delta x = 50$  [m].

The graphs in [Figure 6.8](#) do not coincide on the grid points because the profiles are computed according [section 4.5](#). The initial condition is defined by:

$$u_{itgiven} = \begin{cases} 0, & 0 < 1250, [\text{m}] \\ \left( \frac{1}{2} + \frac{1}{2} \cos(5k_{env}(x - x_{cent})) \right) \times \\ \left( \frac{1}{2} + \frac{1}{2} \cos(k_{env}(x - x_{cent})) \right) & 1250 < 3750, [\text{m}] \\ 0, & 3750 < 10000, [\text{m}] \end{cases} \quad (6.6)$$

with

$x_{cent}$  Location of the centre of the envelope.

$L_{env}$  Length of the envelope.

$k_{env}$   $k_{env} = 2\pi/L_{env}$ .

#### Numerical experiment

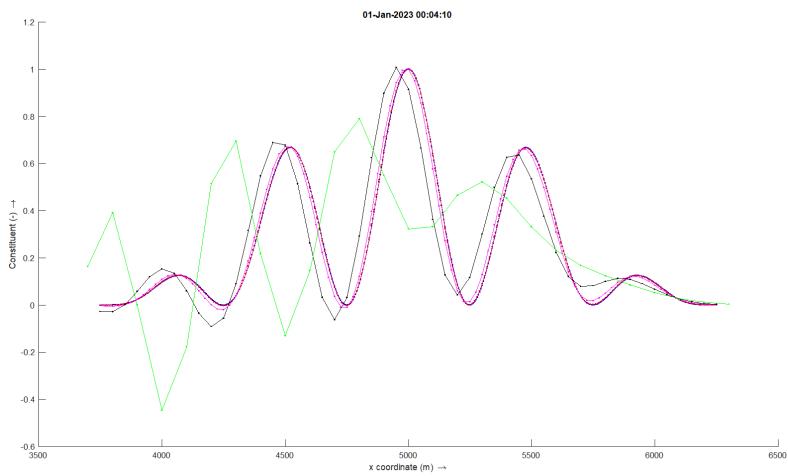
The numerical experiment is performed with the following parameters:

- Length of the domain  $L_x = 10\ 000$  [m].
- Length of the envelope 2500 [m], ranging from 1250 [m] to 3750 [m].
- Grid size and time step,
  - $\Delta x = 5$  [m] and  $\Delta t = 0.01$  [s]
  - $\Delta x = 10$  [m] and  $\Delta t = 0.01$  [s]
  - $\Delta x = 25$  [m] and  $\Delta t = 0.01$  [s]

- $\Delta x = 50$  [m] and  $\Delta t = 0.01$  [s]
- $\Delta x = 100$  [m] and  $\Delta t = 0.01$  [s]
- Start time,  $t_{start} = 0$  [s].
- End time,  $t_{stop} = 250$  [s].
- Prescribed boundary conditions:  $c(0, t) = c(L_x, t) = 0$ .
- **No regularization is applied.**

### Results of the numerical experiments

Results for the four different computations are shown in [Figure 6.9](#)



**Figure 6.9:** Wave package experiment, results at  $t = 250$  [s] and  $\Delta t = 0.01$  [s]: **Blue:**  $\Delta x = 5$  [m], **Red:**  $\Delta x = 10$  [m], **Cyan:**  $\Delta x = 25$  [m], **Black:**  $\Delta x = 50$  [m], **Green:**  $\Delta x = 100$  [m].

#### 6.2.4 Transport of strictly positive constituent

When  $c$  needs a strictly positive value (like a concentration) then due to numerical discretization the value  $c$  could become negative, even if the initial and boundary values are positive. In certain applications a positive value is required and even small negative are not allowed. To ensure the positivity of the constituent  $c$  we will write the equation with variable  $\phi$ , where  $\phi$  is defined as:

$$c = \exp(\ln(c)) = \exp(\phi), \quad \text{with} \quad \phi = \ln(c) \quad (6.7)$$

The considered advection-diffusion equation than reads:

$$\int_{\Omega} \frac{\partial e^{\phi}}{\partial t} d\omega + \int_{\Omega} \frac{\partial (ue^{\phi})}{\partial x} d\omega - \int_{\Omega} \frac{\partial}{\partial x} \left( \varepsilon \frac{\partial e^{\phi}}{\partial x} \right) d\omega = 0, \quad (6.8)$$

With initial condition for the velocity  $u_{given} = 10$  [ $\text{m s}^{-1}$ ], which coincide with the wave celerity in the next numerical experiments.

$$u(x, 0) = u_{given} \quad (6.9)$$

and with a prescribed boundary condition for the constituent  $c$  at the left side of the domain

$$c(0, t) = c_{given} \begin{cases} \frac{1}{2} \cos \left( \pi \left( \frac{t_{reg}-t}{t_{reg}} \right) + 1 \right) & \text{if } t < t_{reg}, \\ 1 & \text{if } t \geq t_{reg}, \end{cases} \quad (6.10)$$

where

$t_{reg}$  The regularization time for the given time-series, [s]

A value of  $c(0, t) = 0$  is estimated by:

$$\phi(0, t) = \ln(c(0, t)) \gtrsim -25 \quad (6.11)$$

### Numerical experiment

The numerical experiment is performed with the following parameters:

- Length of the domain, 12 000 [m]
- Grid size,  $\Delta x = 10$  [m]
- Start time,  $t_{start} = 0$  [s]
- End time,  $t_{stop} = 3600$  [s]
- Timestep,  $\Delta t = 5$  [s]
- Regularization time for time-series,  $t_{reg} = 300$  [s]
- Prescribed constant velocity,  $u_{given}(x, t) = 10$  [ $\text{m s}^{-1}$ ]
- Prescribed initial value of the constituent,  $c(x, 0) = 1.4 \times 10^{-11}$ , so  $\phi = -25$  [-].
- Prescribed constant constituent on boundary  $c_{given}(0, t) = 1$ , so  $\phi = \ln(c_{given}(0, t)) = \ln(1) = 0$  [-]

### Results of the numerical experiments

**Not yet documented**

## 6.3 1-D Advection-diffusion equation

In this section we will show the results of the advection-diffusion equation with a Dirichlet boundary conditions at both sides of the domain and an interface problem, i.e. a large jump of the diffusion coefficient in the middle of the domain.

The considered advection-diffusion equation reads:

$$\frac{\partial c}{\partial t} + \frac{\partial u c}{\partial x} - \frac{\partial}{\partial x} \left( (\varepsilon + \Psi) \frac{\partial c}{\partial x} \right) = 0, \quad u > 0. \quad (6.12)$$

where

$c$	Constituent, [–].
$u$	Advection velocity, [ $\text{m s}^{-1}$ ].
$\varepsilon$	Diffusion coefficient, [ $\text{m}^2 \text{s}^{-1}$ ].
$\Psi$	Artificial diffusion, [ $\text{m}^2 \text{s}^{-1}$ ].

### 6.3.1 Outflow boundary layer

The Dirichlet value at the outflow boundary is so chosen that there will appear an outflow boundary layer. Due to this outflow boundary the numerical scheme need to have a cell Péclet number ( $Pe = u\Delta x/\varepsilon$ ) smaller then two in the vicinity of that layer. In the  $\Delta$ -formulation that will be reach by a regularization step, i.e. increase the diffusion in the vicinity of the boundary layer. To force a outflow boundary layer at both boundaries a Dirichlet boundary is prescribed. With the boundary conditions  $c(0, t) = a$  and  $c(L, t) = b$  the analytic solution read:

$$c(x) = a + (b - a) \frac{e^{\frac{(x-L)}{L}Pe} - e^{-Pe}}{1 - e^{-Pe}}, \quad (6.13)$$

with  $Pe = uL/\varepsilon$ .

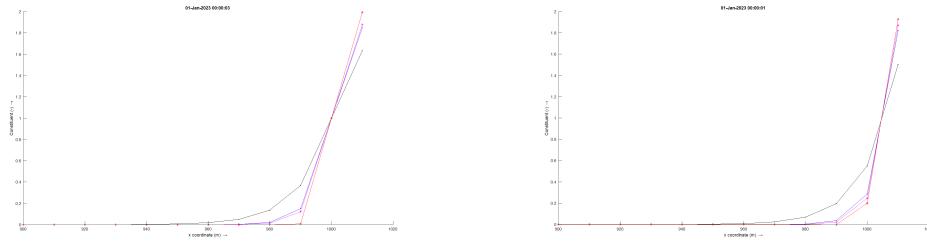
#### Numerical experiment

The numerical experiment is performed with the following parameters:

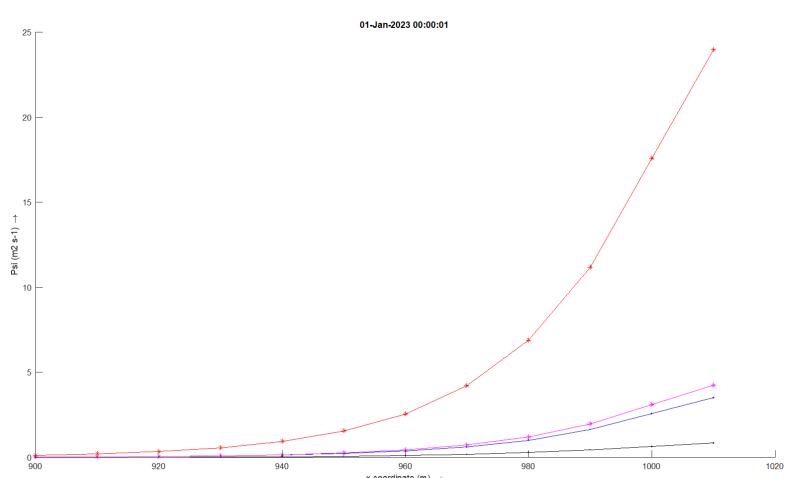
- Length of the domain  $L_x = 1000$  [m].
- Stationary simulation,  $\partial c / \partial t = 0$ .
- Prescribed boundary conditions:  $c(0, t) = 0$  and  $c(L_x, t) = 1$ .
- Grid size  $\Delta x = 10$  [m],
- Diffusion coefficient  $\varepsilon = 10$  [ $\text{m}^2 \text{s}^{-1}$ ]
- Advection velocities,  $Pe = u\Delta x/\varepsilon$ :
  - $u = 1$  [ $\text{m s}^{-1}$ ]  $\rightarrow Pe = 1.0$
  - $u = 1.9$  [ $\text{m s}^{-1}$ ]  $\rightarrow Pe = 1.9$
  - $u = 2.1$  [ $\text{m s}^{-1}$ ]  $\rightarrow Pe = 2.1$
  - $u = 5.0$  [ $\text{m s}^{-1}$ ]  $\rightarrow Pe = 5.0$
- Smoothing factor,  $c_\Psi = 4$
- Right hand side to compute artificial viscosity,  $\frac{1}{32}c_\Psi u\Delta x \partial^2 c / \partial \xi^2$  (educational guess).

## Results of the numerical experiments

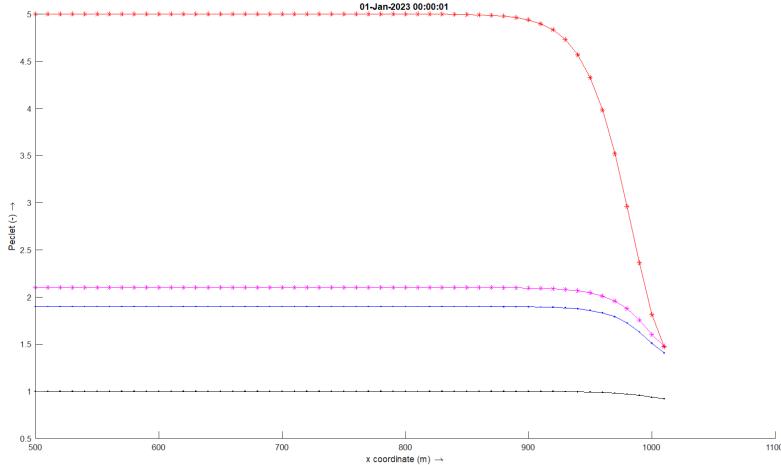
Map results are presented for the constituent  $c$  and the artificial diffusion  $\Psi$ .



**Figure 6.10:** Map results for different values of the advection velocity (thus Péclet number). The graphs with an asterisk represent results with a cell Péclet number larger than two. Black:  $Pe = 1.0$ ; Blue:  $Pe = 1.9$ , Green:  $Pe = 2.1$ ; Cyan:  $Pe = 5.0$ .



**Figure 6.11:** Map results for the used artificial diffusion  $\Psi$ . Black:  $Pe = 1.0$ ; Blue:  $Pe = 1.9$ , Green:  $Pe = 2.1$ ; Cyan:  $Pe = 5.0$ .



**Figure 6.12:** Map results for the used cell Péclet number. Black:  $Pe = 1.0$ ; Blue:  $Pe = 1.9$ , Green:  $Pe = 2.1$ ; Cyan:  $Pe = 5.0$ .

### 6.3.2 Interface problem

A numerical experiments is performed for the stationary advection-diffusion equation with a jump in the diffusion coefficient as described by:

$$\varepsilon(x) = \begin{cases} \check{\varepsilon}, & \text{if } 0 < x \leq x^*, \\ 1, & \text{if } x^* < x < 1 \end{cases} \quad (6.14)$$

An analytical solution exists in case  $u = 0$  and read (Wesseling, 2001, eq. 3.11):

$$c(x) = \begin{cases} \alpha x, & \text{if } 0 < x \leq x^*, \\ \check{\varepsilon}\alpha x + 1 - \check{\varepsilon}\alpha, & \text{if } x^* < x < 1 \end{cases} \quad (6.15)$$

$$\alpha = \frac{1}{x^* - \check{\varepsilon}x^* + \check{\varepsilon}} \quad (6.16)$$

- If  $\varepsilon \frac{\partial c}{\partial x} \equiv 0$  then either  $\varepsilon = 0$  or  $\frac{\partial c}{\partial x} = 0$ . Where  $\varepsilon = 0$  is not feasible.

Some numerical experiments are performed with several values of  $u$ .

#### Numerical experiment

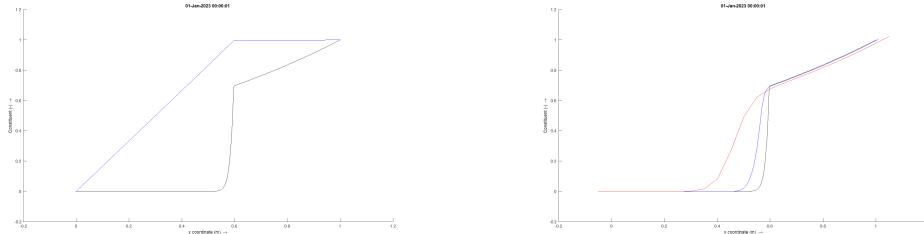
The numerical experiment is performed with the following parameters:

- Length of the domain  $L_x = 1$  [m].
- Stationary simulation,  $\partial c / \partial t = 0$ .
- Prescribed boundary conditions:  $c(0, t) = 0$  and  $c(L_x, t) = 1$ .
- Grid size:
  - $\Delta x = 0.001$  [m]  $\rightarrow Pe = 0.09$ ,
  - $\Delta x = 0.01$  [m]  $\rightarrow Pe = 0.9$ ,

- $\Delta x = 0.05 \text{ [m]} \rightarrow Pe = 4.5$ ,
- Diffusion coefficient  $\xi = 0.01 \text{ [m}^2 \text{s}^{-1}]$
- Advection velocities,  $Pe = u\Delta x/\xi$ :
  - $u = 0 \text{ [m s}^{-1}] \rightarrow Pe = 0.0$
  - $u = 0.9 \text{ [m s}^{-1}] \rightarrow Pe = 0.09, Pe = 0.9$  and  $Pe = 4.5$

### Results of numerical experiment

Map results are presented for the constituent  $c$  and the artificial diffusion  $\Psi$ .



**(a)** High numerical resolution solution  $\Delta x = 0.001 \text{ [m]}$ . Blue:  $u = 0 \text{ [m s}^{-1}]$  and Black:  $u = 0.9 \text{ [m s}^{-1}]$ .

**(b)** Numerical solution,  $u = 0.9 \text{ [m s}^{-1}]$ . Black:  $\Delta x = 0.001 \text{ [m]} \rightarrow Pe = 0.09$ ; Blue:  $\Delta x = 0.01 \text{ [m]} \rightarrow Pe = 0.9$  and Red:  $\Delta x = 0.05 \text{ [m]} \rightarrow Pe = 4.5$ .

**Figure 6.13:** Map results for different values of the Péclet number.

## 6.4 1-D Wave equation

### 6.4.1 Gaussian hump

The considered 1-D wave equation reads:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = 0 \quad \text{continuity eq.} \quad (6.17)$$

$$\frac{\partial q}{\partial t} + gh \frac{\partial h}{\partial x} = 0 \quad \text{momentum eq.} \quad (6.18)$$

With initial conditions

$$h(x, 0) = \zeta(x, 0) - z_b(x), \quad [\text{m}] \quad (6.19)$$

$$q(x, 0) = 0, \quad [\text{m}^2 \text{s}^{-1}] \quad (6.20)$$

for the the water level a Gaussian hump is prescribed

$$\zeta(x) = 2a_0 \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right), \quad [\text{m}] \quad (6.21)$$

At the boundaries no ingoing signals are prescribed, so outgoing signals are leaving the domain unhampered, which means no reflections will be present other then numerical reflections.

### Numerical experiment

The numerical experiment is performed with the following parameters:

- Length of the domain,  $L_x = 12\,000$  [m], ranging from  $-6000$  [m] to  $6000$  [m].
- Bed level,  $z_b = -10$  [m].
- Grid size,  $\Delta x = 10$  [m].
- Start time,  $t_{start} = 0$  [s].
- End time,  $t_{stop} = 3600$  [s].
- Timestep,  $\Delta t = 10$  [s].
- Regularization time for time-series,  $t_{reg} = 300$  [s].
- Amplitude of the Gaussian hump at the boundary,  $a_0 = 0.01$  [m].
- Centre of the Gaussian hump,  $\mu = 3000$  [m].
- Spreading of the Gaussian hump,  $\sigma = 700$  [m].

And a second experiment with given boundary values:

- Prescribed discharge boundary at  $-6000$  [m]:  $q(0, t) = 0.05$  [ $\text{m}^2 \text{s}^{-1}$ ].
- Prescribed water level boundary value at  $6000$  [m]:  $\zeta(0, t) = 0.02$  [m].

Because the boundary values are constant in time the solution is time-independent.

Therefore two simulation should be performed:

- 1 A stationary computation (with  $\Delta t = 0$  [s]) and
- 2 an temporal computation (with  $t_{stop} = 10\,800$  [s])

### Results of the numerical experiments 1

**Not yet documented**

### Results of the numerical experiments 2

**Not yet documented**

## 6.4.2 Weir

The model is taken from [Borsboom \(2001\)](#). The considered 1-D wave equation reads:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = 0, \quad \text{continuity eq.} \quad (6.22)$$

$$\frac{\partial q}{\partial t} + \frac{\partial(q^2/h)}{\partial x} + gh \frac{\partial h}{\partial x} - \frac{\partial}{\partial x} \left( (\nu + \Psi) h \frac{\partial(q/h)}{\partial x} \right) = 0, \quad \text{momentum eq.} \quad (6.23)$$

- Length of the domain,  $500$  [m].
- Artificial viscosity  $\Psi$  computated as presented in [section 4.2](#).

Bathymetry [m]:

$$z_b(x) = \begin{cases} -12 & 0 < x \leq 200, \\ -12 + 7(x - 200)/50 & 200 < x \leq 250, \\ -5 & 250 < x \leq 350, \\ -5 - 5(x - 350)/100 & 350 < x \leq 450, \\ -10 & 450 < x \leq 500. \end{cases} \quad (6.24)$$

Initial conditions

$$h(x, 0) = 0, \quad (6.25)$$

$$q(x, 0) = 0 \quad (6.26)$$

Boundary conditions

- Prescribed discharge boundary at 0 [m]:  $q(0, t) = 19.8656 \text{ [m}^2 \text{s}^{-1}\text{]}$ .
- Prescribed water level boundary value at 500 [m]:  $\zeta(500, t) = -3 \text{ [m]}$ .

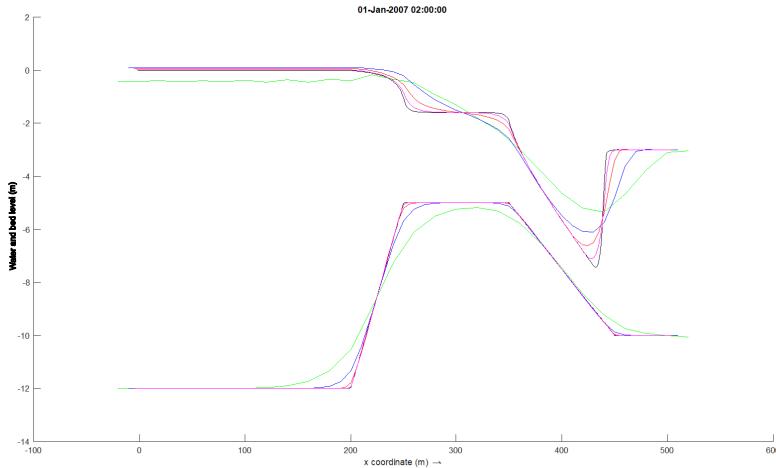
### *Numerical experiment*

The numerical experiment is performed with the following parameters:

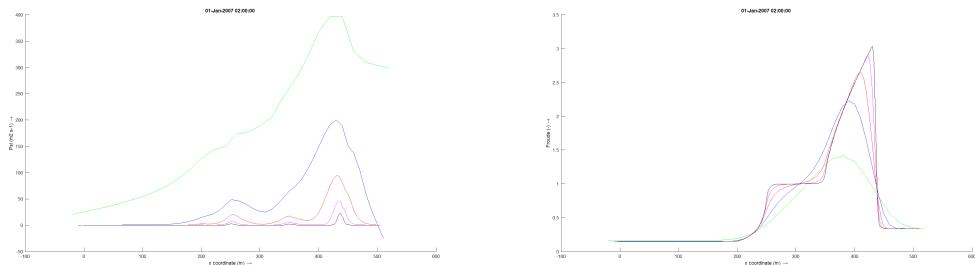
- Grid size and time step,
  - $\Delta x = 10 \text{ [m]}$  and  $\Delta t = 2 \text{ [s]}$
  - $\Delta x = 5 \text{ [m]}$  and  $\Delta t = 1 \text{ [s]}$
  - $\Delta x = 2.5 \text{ [m]}$  and  $\Delta t = 0.5 \text{ [s]}$
  - $\Delta x = 1.25 \text{ [m]}$  and  $\Delta t = 0.25 \text{ [s]}$
- Start time,  $t_{start} = 0 \text{ [s]}$ .
- End time,  $t_{stop} = 7200 \text{ [s]}$ .
- Regularization time for time-series,  $t_{reg} = 300 \text{ [s]}$ .
- Kinematic viscosity,  $\nu = 0.01 \text{ [m}^2 \text{s}^{-1}\text{]}$
- $\varepsilon_{bc} = 1 \times 10^{-2}$

### *Results of the numerical experiments*

Results for the four different computations are shown in [Figure 6.14](#)



**Figure 6.14:** Top graphs present the water level. Lower graphs present the regularized bathymetry. Green:  $\Delta x = 20$  [m],  $\Delta t = 4$  [s]; Blue:  $\Delta x = 10$  [m],  $\Delta t = 2$  [s]; Red:  $\Delta x = 5$  [m],  $\Delta t = 1$  [s]; Cyan:  $\Delta x = 2.5$  [m],  $\Delta t = 0.5$  [s]; Black:  $\Delta x = 1.25$  [m],  $\Delta t = 0.25$  [s]



**(a)** Artificial viscosity  $\Psi$ .

**(b)** Froude number.

**Figure 6.15:** Artificial viscosity  $\Psi$  and Froude number. Green:  $\Delta x = 20$  [m],  $\Delta t = 4$  [s]; Blue:  $\Delta x = 10$  [m],  $\Delta t = 2$  [s]; Red:  $\Delta x = 5$  [m],  $\Delta t = 1$  [s]; Cyan:  $\Delta x = 2.5$  [m],  $\Delta t = 0.5$  [s]; Black:  $\Delta x = 1.25$  [m],  $\Delta t = 0.25$  [s]

# **2D Wave**

## 7 2D Shallow water equations

Consider the non-linear shallow water equation

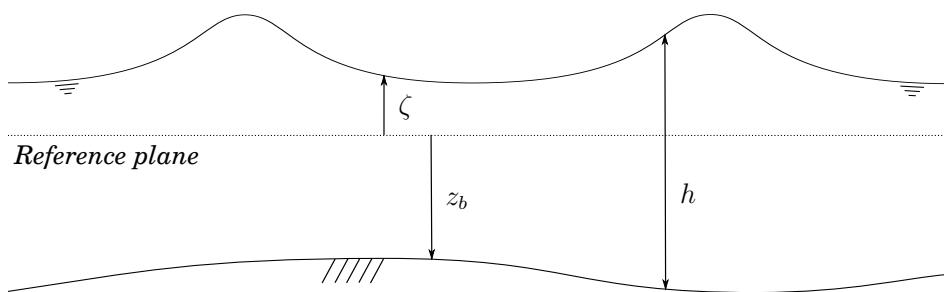
$$\frac{\partial h}{\partial t} + \nabla \cdot \mathbf{q} = 0, \quad (7.1a)$$

$$\begin{aligned} \frac{\partial \mathbf{q}}{\partial t} + \nabla \cdot \left( \frac{\mathbf{q} \mathbf{q}^T}{h} \right) + gh \nabla \zeta + \\ + c_f \left( \frac{\mathbf{q} |\mathbf{q}|}{h^2} \right) - \nabla \cdot (\nu h (\nabla \mathbf{q}/h + \nabla \mathbf{q}^T/h)) = 0, \end{aligned} \quad (7.1b)$$

$$\zeta = h + z_b, \quad (7.1c)$$

with

$\zeta$	Water level w.r.t. reference plane ( $\zeta = h + z_b$ ), [m].
$h$	Water depth ( $h = \zeta - z_b$ ), [m].
$z_b$	Bed level w.r.t. reference plane, [m].
$\mathbf{q}$	Flow, defined as $\mathbf{q} = (q, r)^T = (hu, hv)^T$ , [ $\text{m}^2 \text{s}^{-1}$ ].
$\mathbf{u}$	Velocity vector, defined as $\mathbf{u} = (u, v)^T$ , [ $\text{m s}^{-1}$ ].
$c_f$	Bed shear stress coefficient, [-].
	Chézy: $c_f = g/C^2$
$C$	Chézy coefficient, [ $\text{m}^{1/2} \text{s}^{-1}$ ].
$g$	Acceleration due to gravity, [ $\text{m s}^{-2}$ ].
$\nu$	Kinematic viscosity, [ $\text{m}^2 \text{s}^{-1}$ ].



**Figure 7.1:** Definition sketch of water level ( $\zeta$ ), bed level ( $z_b$ ) and total water depth ( $h$ )

The 'linear' shallow water equations in curvilinear coordinates read:

$$J \frac{\partial h}{\partial t} + \frac{\partial}{\partial \xi} (y_\eta q - x_\eta r) + \frac{\partial}{\partial \eta} (-y_\xi q + x_\xi r) = 0, \quad (7.2)$$

$$J \frac{\partial q}{\partial t} + gh \left( y_\eta \frac{\partial \zeta}{\partial \xi} - y_\xi \frac{\partial \zeta}{\partial \eta} \right) = 0, \quad q\text{-momentum eq.} \quad (7.3)$$

$$J \frac{\partial r}{\partial t} + gh \left( -x_\eta \frac{\partial \zeta}{\partial \xi} + x_\xi \frac{\partial \zeta}{\partial \eta} \right) = 0, \quad r\text{-momentum eq.} \quad (7.4)$$

## Finite Volume approach

Integrating the equations over a finite volume  $\Omega$  yields:

$$\int_{\Omega} \frac{\partial h}{\partial t} d\omega + \int_{\Omega} \nabla \cdot \mathbf{q} d\omega = 0, \quad (7.5a)$$

$$\begin{aligned} \int_{\Omega} \frac{\partial \mathbf{q}}{\partial t} d\omega + \int_{\Omega} \nabla \cdot \left( \frac{\mathbf{q} \mathbf{q}^T}{h} \right) d\omega + \int_{\Omega} gh \nabla \zeta d\omega + \\ + \int_{\Omega} c_f \left( \frac{\mathbf{q} |\mathbf{q}|}{h^2} \right) d\omega - \int_{\Omega} \nabla \cdot (\nu h (\nabla \mathbf{q}/h + \nabla \mathbf{q}^T/h)) d\omega = 0, \end{aligned} \quad (7.5b)$$

$$\int_{\Omega} \zeta d\omega = \int_{\Omega} h d\omega + \int_{\Omega} z_b d\omega, \quad (7.5c)$$

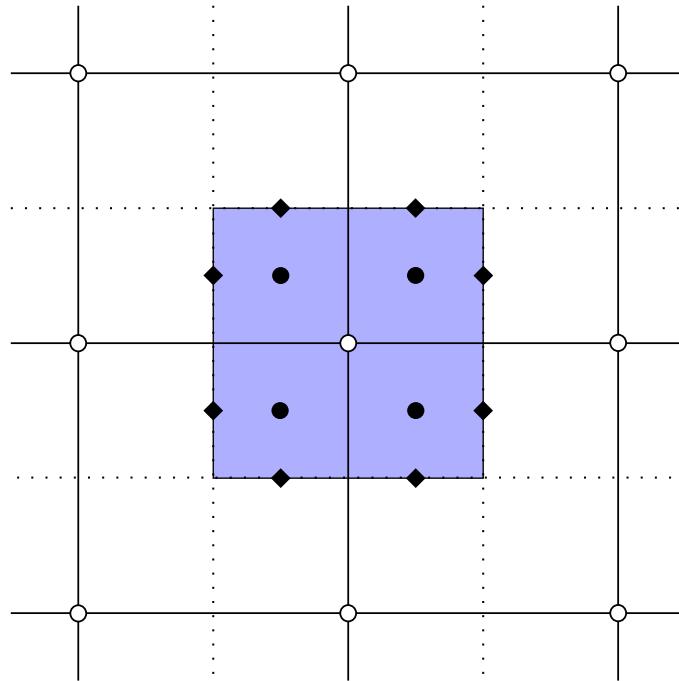
Integrating the 'linear' shallow water equations in curvilinear coordinates over a finite volume  $\Omega_{\xi\eta}$  yields:

$$\int_{\Omega_{\xi\eta}} \left[ J \frac{\partial h}{\partial t} + \frac{\partial}{\partial \xi} (y_\eta q - x_\eta r) + \frac{\partial}{\partial \eta} (-y_\xi q + x_\xi r) \right] d\xi d\eta = 0, \quad (7.6)$$

$$\int_{\Omega_{\xi\eta}} \left[ J \frac{\partial q}{\partial t} + gh \left( y_\eta \frac{\partial \zeta}{\partial \xi} - y_\xi \frac{\partial \zeta}{\partial \eta} \right) \right] d\xi d\eta = 0, \quad q\text{-momentum eq.} \quad (7.7)$$

$$\int_{\Omega_{\xi\eta}} \left[ J \frac{\partial r}{\partial t} + gh \left( -x_\eta \frac{\partial \zeta}{\partial \xi} + x_\xi \frac{\partial \zeta}{\partial \eta} \right) \right] d\xi d\eta = 0, \quad r\text{-momentum eq.} \quad (7.8)$$

## 7.1 Space discretization, structured grid



**Figure 7.2:** Definition of the control volume in a structured grid to solve the 2D-shallow water equations in the interior area. The black dots indicate the location of the quadrature points for the sources, and black diamonds for the flux points.

For the space discretizations of an arbitrary function  $u$  on the quadrature point of a sub-control volume the following space interpolations are used,  $u \in \{h, q, r\}$  (1-point Gauss):

$$u|_{i+\frac{1}{4}, j+\frac{1}{4}} \approx \frac{1}{16} (9u_{i,j} + 3u_{i+1,j} + u_{i+1,j+1} + 3u_{i,j+1}) \quad (7.9)$$

and flux points

$$u|_{i+\frac{1}{2}, j+\frac{1}{4}} \approx \frac{1}{8} (3u_{i,j} + 3u_{i+1,j} + u_{i+1,j+1} + u_{i,j+1}) \quad (7.10)$$

$$u|_{i+\frac{1}{4}, j+\frac{1}{2}} \approx \frac{1}{8} (3u_{i,j} + u_{i+1,j+1} + u_{i+1,j} + 3u_{i,j+1}) \quad (7.11)$$

See for the locations Figure 7.2.

### 7.1.1 Discretization continuity equation

The discretization of continuity equation (equation (7.6)) will be presented term by term.

### 7.1.1.1 Time derivative

The time derivative term of the continuity equation reads:

$$\int_{\Omega_{\xi\eta}} J \frac{\partial h}{\partial t} d\xi d\eta \quad (7.12)$$

which will be approximated by the sum of the integral over the sub-control volumes, with taking into account that the Jacobian  $J$  is constant in time. On a structured grid one control volume ( $cv$ ) around a node consist of four sub-control volumes ( $scv_i, i \in \{0, 1, 2, 3\}$ ).

$$\begin{aligned} J_{cv} \int_{cv} \frac{\partial h}{\partial t} d\omega &= J_{scv_0} \int_{scv_0} \frac{\partial h}{\partial t} d\omega + J_{scv_1} \int_{scv_1} \frac{\partial h}{\partial t} d\omega + \\ &+ J_{scv_2} \int_{scv_2} \frac{\partial h}{\partial t} d\omega + J_{scv_3} \int_{scv_3} \frac{\partial h}{\partial t} d\omega \end{aligned} \quad (7.13)$$

For the discretization on a curvilinear grid we get:

$$\begin{aligned} J_{cv} \int_{cv} \frac{\partial h}{\partial t} d\omega &\approx J_{scv_0} \Delta t_{inv} \left( h_{i-\frac{1}{4}, j-\frac{1}{4}}^{n+1, p+1} - h_{i-\frac{1}{4}, j-\frac{1}{4}}^{n+1, n} \right) + \\ &J_{scv_1} \Delta t_{inv} \left( h_{i+\frac{1}{4}, j-\frac{1}{4}}^{n+1, p+1} - h_{i+\frac{1}{4}, j-\frac{1}{4}}^{n+1, n} \right) + \\ &J_{scv_2} \Delta t_{inv} \left( h_{i+\frac{1}{4}, j+\frac{1}{4}}^{n+1, p+1} - h_{i+\frac{1}{4}, j+\frac{1}{4}}^{n+1, n} \right) + \\ &J_{scv_3} \Delta t_{inv} \left( h_{i-\frac{1}{4}, j+\frac{1}{4}}^{n+1, p+1} - h_{i-\frac{1}{4}, j+\frac{1}{4}}^{n+1, n} \right) \end{aligned} \quad (7.14)$$

with  $J_{scv_i}$  the area of the sub control volume  $i$ . For cartesian grids we have  $J_{scv_i} = \frac{1}{4} \Delta x \Delta y$ .

Just looking to the quadrature point of  $scv_2$  as part of the control volume for node  $(i, j)$  the discretization reads:

$$J_{scv_2} \Delta t_{inv} \left( h_{i+\frac{1}{4}, j+\frac{1}{4}}^{n+1} - h_{i+\frac{1}{4}, j+\frac{1}{4}}^n \right) = \quad (7.15)$$

$$= J_{scv_2} \Delta t_{inv} \left[ \frac{1}{16} (9h_{i,j}^{n+1} + 3h_{i+1,j}^{n+1} + 3h_{i,j+1}^{n+1} + h_{i+1,j+1}^{n+1}) + \right. \quad (7.16)$$

$$\left. - \frac{1}{16} (9h_{i,j}^n + 3h_{i+1,j}^n + 3h_{i,j+1}^n + h_{i+1,j+1}^n) \right] \quad (7.17)$$

Written in  $\Delta$ -formulation it yields (using  $\Delta h^{n+1, p+1} = \Delta h$ ):

$$J_{scv_2} \Delta t_{inv} \left( h_{i+\frac{1}{4}, j+\frac{1}{4}}^{n+1} - h_{i+\frac{1}{4}, j+\frac{1}{4}}^n \right) = \quad (7.18)$$

$$= J_{scv_2} \Delta t_{inv} \left[ \frac{1}{16} (9\Delta h_{i,j} + 3\Delta h_{i+1,j+1} + 3\Delta h_{i,j+1} + \Delta h_{i+1,j+1}) \right] +$$

$$\begin{aligned} &+ J_{scv_2} \Delta t_{inv} \left[ \frac{1}{16} \left( 9(h_{i,j}^{n+1, p} - h_{i,j}^n) + 3(h_{i+1,j}^{n+1, p} - h_{i+1,j}^n) + \right. \right. \\ &\left. \left. 3(h_{i,j+1}^{n+1, p} - h_{i,j+1}^n) + (h_{i+1,j+1}^{n+1, p+1} - h_{i+1,j+1}^n) \right) \right] \end{aligned} \quad (7.19)$$

with

$$J_{scv_2} = x_\xi y_\eta - y_\xi x_\eta \quad (7.20)$$

with  $J_{scv_2}$  representing the area of  $scv_2$ , this area is computed by

$$J = \frac{1}{2} \sum_{i=0}^3 (x_i y_{i+1} - x_{i+1} y_i), \quad \text{with } x_4 = x_0 \text{ and } y_4 = y_0 \quad (7.21)$$

### 7.1.1.2 Mass flux

The discretization of the mass flux term of the continuity equation

$$\oint_{\partial\Omega_{\xi\eta}} ((y_\eta q - x_\eta r) n_\xi + (-y_\xi q + x_\xi r) n_\eta) dl \quad (7.22)$$

will be given in this section (equation (A.25)), multiplied by  $J$ ). Where  $\mathbf{n} = (n_\xi, n_\eta)^T$  is the outward normal vector.

The linearization around an iteration step yields (using  $\Delta q^{n+1,p+1} = \Delta q$  and  $\Delta r^{n+1,p+1} = \Delta r$ ):

$$\begin{aligned} & \oint_{\partial\Omega_{\xi\eta}} \left[ (y_\eta (q^{n+\theta,p} + \theta\Delta q) - x_\eta (r^{n+\theta,p} + \theta\Delta r)) n_\xi \right. \\ & \quad \left. + (-y_\xi (q^{n+\theta,p} + \theta\Delta q) + x_\xi (r^{n+\theta,p} + \theta\Delta r)) n_\eta \right] dl \end{aligned} \quad (7.23)$$

This terms need to be computed for each of the eight control volume faces, taking into account the outward normal. For the quadrature point  $(i + \frac{1}{2}, j + \frac{1}{4})$  where  $\mathbf{n} = (n_\xi, n_\eta)^T = (1, 0)^T$  and  $\|dl\| = \frac{1}{2}$  it reads:

$$(y_\eta (q^{n+\theta,p} + \theta\Delta q) - x_\eta (r^{n+\theta,p} + \theta\Delta r)) n_\xi \|dl\| \approx \quad (7.24)$$

$$\approx \left[ \frac{1}{2} y_\eta (q^{n+\theta,p} + \theta\Delta q) - \frac{1}{2} x_\eta (r^{n+\theta,p} + \theta\Delta r) \right] n_\xi \quad (7.25)$$

$\Leftrightarrow$

$$\left[ \frac{1}{2} y_\eta \theta\Delta q - \frac{1}{2} x_\eta \theta\Delta r + \frac{1}{2} y_\eta q^{n+\theta,p} - \frac{1}{2} x_\eta r^{n+\theta,p} \right] n_\xi \quad (7.26)$$

with

$$y_\eta|_{i+\frac{1}{2},j+\frac{1}{4}} = \frac{1}{2} (y_{i,j+1} - y_{i,j}) + \frac{1}{2} (y_{i+1,j+1} - y_{i+1,j}) \quad (7.27)$$

$$x_\eta|_{i+\frac{1}{2},j+\frac{1}{4}} = \frac{1}{4} (3(x_{i+1,j} - x_{i,j}) + (x_{i+1,j+1} - x_{i,j+1})) \quad (7.28)$$

and for terms related to  $q$  we get (similar for  $r$ ):

$$q|_{i+\frac{1}{2},j+\frac{1}{4}}^{n+\theta,p} = \frac{1}{8} (3q_{i,j}^{n+\theta,p} + 3q_{i+1,j}^{n+\theta,p} + 1q_{i,j+1}^{n+\theta,p} + 1q_{i+1,j+1}^{n+\theta,p}) \quad (7.29)$$

$$\theta\Delta q|_{i+\frac{1}{2},j+\frac{1}{4}} = \theta \frac{1}{8} (3\Delta q_{i,j} + 3\Delta q_{i+1,j} + 1\Delta q_{i,j+1} + 1\Delta q_{i+1,j+1}) \quad (7.30)$$

Equation (7.29) is part of the right hand side and equation (7.30) is a part of the matrix coefficients.

## 7.1.2 Discretizations momentum equations

The discretization of momentum [equation \(7.5b\)](#) will be presented term by term.

### 7.1.2.1 Time derivative

The time derivative term of both momentum equations is similar as for the continuity equation, see [section 7.1.1.1](#). The time derivative for the  $q$ -momentum equation reads:

$$J \int_{\Omega} \frac{\partial q}{\partial t} d\omega, \quad q\text{-momentum eq.} \quad (7.31)$$

and for the  $r$ -momentum equation reads:

$$J \int_{\Omega} \frac{\partial r}{\partial t} d\omega. \quad r\text{-momentum eq.} \quad (7.32)$$

### 7.1.2.2 Pressure term

In this section we use that the pressure term is dependent on  $\zeta$  and read (already multiplied by  $J$ )

$$gh \left( y_{\eta} \frac{\partial \zeta}{\partial \xi} - y_{\xi} \frac{\partial \zeta}{\partial \eta} \right), \quad q\text{-momentum eq.} \quad (7.33)$$

$$gh \left( -x_{\eta} \frac{\partial \zeta}{\partial \xi} + x_{\xi} \frac{\partial \zeta}{\partial \eta} \right). \quad r\text{-momentum eq.} \quad (7.34)$$

The discretization of these terms will be given in this section. The integral over a control volume will be the sum of integrals over the sub control volumes. On a structured grid one control volume ( $cv$ ) around a node consist of four sub-control volumes ( $scv_i$ ,  $i \in \{0, 1, 2, 3\}$ ). Thus

$$gh \mathbf{T} \nabla \zeta|_{sc} = gh \mathbf{T} \nabla \zeta|_{scv_0} + gh \mathbf{T} \nabla \zeta|_{scv_1} + gh \mathbf{T} \nabla \zeta|_{scv_2} + gh \mathbf{T} \nabla \zeta|_{scv_3} \quad (7.35)$$

with the tensor  $\mathbf{T}$  defined as:

$$\mathbf{T} = \begin{pmatrix} y_{\eta} & -y_{\xi} \\ -x_{\eta} & x_{\xi} \end{pmatrix} = J \frac{1}{J} \begin{pmatrix} y_{\eta} & -y_{\xi} \\ -x_{\eta} & x_{\xi} \end{pmatrix}, \quad \text{see } \text{equation (A.5)} \quad (7.36)$$

#### *q-momentum*

Considering one sub-control volume and only for the  $x$ -direction (similar for the  $r$ -momentum) then the linearization in time reads:

$$gh \left( y_{\eta} \frac{\partial \zeta}{\partial \xi} - y_{\xi} \frac{\partial \zeta}{\partial \eta} \right) \approx \quad (7.37)$$

$$\approx g (h_{qp}^{n+\theta,p} + \theta \Delta h_{qp}) \times \quad (7.38)$$

$$\times \left( y_{\eta_{qp}} \frac{\partial}{\partial \xi} (\zeta_{qp}^{n+\theta,p} + \theta \Delta \zeta_{qp}) - y_{\xi_{qp}} \frac{\partial}{\partial \eta} (\zeta_{qp}^{n+\theta,p} + \theta \Delta \zeta_{qp}) \right) \quad (7.39)$$

with  $qp$  the location of the quadrature point in the sub-control volume. Assume that the higher order terms are negligible then the discretization for each of the 4 sub-control volumes reads:

$$gh_{qp}^{n+\theta,p} \left( y_{\eta_{qp}} \frac{\partial}{\partial \xi} (\zeta_{qp}^{n+\theta,p}) - y_{\xi_{qp}} \frac{\partial}{\partial \eta} (\zeta_{qp}^{n+\theta,p}) \right) + \quad (7.40)$$

$$+ gh_{qp}^{n+\theta,p} \left( y_{\eta_{qp}} \frac{\partial}{\partial \xi} (\theta \Delta \zeta_{qp}) - y_{\xi_{qp}} \frac{\partial}{\partial \eta} (\theta \Delta \zeta_{qp}) \right) + \quad (7.41)$$

$$+ g \left( y_{\eta_{qp}} \frac{\partial}{\partial \xi} (\zeta_{qp}^{n+\theta,p}) - y_{\xi_{qp}} \frac{\partial}{\partial \eta} (\zeta_{qp}^{n+\theta,p}) \right) \theta \Delta h_{qp} \quad (7.42)$$

Just looking to the quadrature point of  $scv_2$  as part of the control volume for node  $(i, j)$  the discretization reads (term by term):

$$h_{i+\frac{1}{4},j+\frac{1}{4}}^{n+\theta,p} \approx \frac{1}{16} \left( 9h_{i,j}^{n+\theta,p} + 3h_{i+1,j}^{n+\theta,p} + h_{i+1,j+1}^{n+\theta,p} + 3h_{i,j+1}^{n+\theta,p} \right) \quad (7.43)$$

$$\frac{\partial \zeta_{i+\frac{1}{4},j+\frac{1}{4}}^{n+\theta,p}}{\partial \xi} \approx [3(\zeta_{i+1,j} - \zeta_{i,j}) + (\zeta_{i+1,j+1} - \zeta_{i,j+1})] \quad (7.44)$$

$$\frac{\partial \zeta_{i+\frac{1}{4},j+\frac{1}{4}}^{n+\theta,p}}{\partial \eta} \approx [3(\zeta_{i,j+1} - \zeta_{i,j}) + (\zeta_{i+1,j+1} - \zeta_{i+1,j})] \quad (7.45)$$

$$\frac{\partial \Delta \zeta_{i+\frac{1}{4},j+\frac{1}{4}}^{n+1,p+1}}{\partial \xi} \approx \frac{1}{4} [3(\Delta \zeta_{i+1,j} - \Delta \zeta_{i,j}) + (\Delta \zeta_{i+1,j+1} - \Delta \zeta_{i,j+1})] \quad (7.46)$$

$$\frac{\partial \Delta \zeta_{i+\frac{1}{4},j+\frac{1}{4}}^{n+1,p+1}}{\partial \eta} \approx \frac{1}{4} [3(\Delta \zeta_{i,j+1} - \Delta \zeta_{i,j}) + (\Delta \zeta_{i+1,j+1} - \Delta \zeta_{i+1,j})] \quad (7.47)$$

$$\Delta h_{i+\frac{1}{4},j+\frac{1}{4}}^{n+1,p+1} \approx \frac{1}{16} (9\Delta h_{i,j} + 3\Delta h_{i+1,j} + \Delta h_{i+1,j+1} + 3\Delta h_{i,j+1}) \quad (7.48)$$

### r-momentum

For the  $r$ -momentum equation:

$$gh \left( -x_\eta \frac{\partial \zeta}{\partial \xi} + x_\xi \frac{\partial \zeta}{\partial \eta} \right) \approx \quad (7.49)$$

$$\approx g (h_{qp}^{n+\theta,p} + \theta \Delta h_{qp}) \times \quad (7.50)$$

$$\times \left( -x_{\eta_{qp}} \frac{\partial}{\partial \xi} (\zeta_{qp}^{n+\theta,p} + \theta \Delta \zeta_{qp}) + x_{\xi_{qp}} \frac{\partial}{\partial \eta} (\zeta_{qp}^{n+\theta,p} + \theta \Delta \zeta_{qp}) \right) \quad (7.51)$$

with  $qp$  the location of the quadrature point in the sub-control volume. The discretization for each of the 4 sub-control volumes reads:

$$gh_{qp}^{n+\theta,p} \left( -x_{\eta_{qp}} \frac{\partial}{\partial \xi} (\zeta_{qp}^{n+\theta,p}) + x_{\xi_{qp}} \frac{\partial}{\partial \eta} (\zeta_{qp}^{n+\theta,p}) \right) + \quad (7.52)$$

$$+ gh_{qp}^{n+\theta,p} \left( -x_{\eta_{qp}} \frac{\partial}{\partial \xi} (\theta \Delta \zeta_{qp}) + x_{\xi_{qp}} \frac{\partial}{\partial \eta} (\theta \Delta \zeta_{qp}) \right) + \quad (7.53)$$

$$+ g \left( -x_{\eta_{qp}} \frac{\partial}{\partial \xi} (\zeta_{qp}^{n+\theta,p}) + x_{\xi_{qp}} \frac{\partial}{\partial \eta} (\zeta_{qp}^{n+\theta,p}) \right) \theta \Delta h_{qp} \quad (7.54)$$

### 7.1.2.3 Convection

The convection term in vector notation reads:

$$\oint_{\partial\Omega_{\xi\eta}} \left[ (y_\eta q - x_\eta r) \frac{q}{h} n_\xi + (-y_\xi q + x_\xi r) \frac{q}{h} n_\eta \right] dl, \quad q\text{-momentum eq.} \quad (7.55)$$

$$\oint_{\partial\Omega_{\xi\eta}} \left[ (y_\eta q - x_\eta r) \frac{r}{h} n_\xi + (-y_\xi q + x_\xi r) \frac{r}{h} n_\eta \right] dl, \quad r\text{-momentum eq.} \quad (7.56)$$

will be given in this section (equation (A.31), multiplied with  $J$ ). Where  $\mathbf{n} = (n_\xi, n_\eta)^T$  is the outward normal vector.

Considering one sub-control volume and only for the  $x$ -direction (similar for the  $y$ -direction) then the time discretization reads:

$$\begin{aligned} \oint_{\partial\Omega_{\xi\eta}} & \left[ (y_\eta (q^{n+\theta,p} + \theta\Delta q) - x_\eta (r^{n+\theta,p} + \theta\Delta r)) \frac{q^{n+\theta,p} + \theta\Delta q}{h^{n+\theta,p} + \theta\Delta h} n_\xi + \right. \\ & \left. + (-y_\xi (q^{n+\theta,p} + \theta\Delta q) + x_\xi (r^{n+\theta,p} + \theta\Delta r)) \frac{q^{n+\theta,p} + \theta\Delta q}{h^{n+\theta,p} + \theta\Delta h} n_\eta \right] dl \end{aligned} \quad (7.57)$$

These terms need to be computed for each of the control volume faces, taken into account the outward normal. Eight faces on a structured grid.

The linearization in time for the  $q$ -momentum equation reads (see equation (3.42)):

$$\frac{1}{2} \left[ (y_\eta q^{n+\theta,p} - x_\eta r^{n+\theta,p}) \frac{q^{n+\theta,p}}{h^{n+\theta,p}} n_\xi + (-y_\xi q^{n+\theta,p} + x_\xi r^{n+\theta,p}) \frac{q^{n+\theta,p}}{h^{n+\theta,p}} n_\eta \right] + \quad (7.58)$$

$$+ \frac{1}{2} \theta \Delta h \left[ \left( \frac{-y_\eta (q^{n+\theta,p})^2 + x_\eta q^{n+\theta,p} r^{n+\theta,p}}{(h^{n+\theta,p})^2} \right) n_\xi + \left( \frac{y_\xi (q^{n+\theta,p})^2 - x_\xi q^{n+\theta,p} r^{n+\theta,p}}{(h^{n+\theta,p})^2} \right) n_\eta \right] + \quad (7.59)$$

$$+ \frac{1}{2} \theta \Delta q \left[ \left( \frac{2y_\eta q^{n+\theta,p} - x_\eta r^{n+\theta,p}}{h^{n+\theta,p}} \right) n_\xi + \left( \frac{-2y_\xi q^{n+\theta,p} + x_\xi r^{n+\theta,p}}{h^{n+\theta,p}} \right) n_\eta \right] + \quad (7.60)$$

$$+ \frac{1}{2} \theta \Delta r \left[ \left( \frac{-x_\eta q^{n+\theta,p}}{h^{n+\theta,p}} \right) n_\xi + \left( \frac{x_\xi q^{n+\theta,p}}{h^{n+\theta,p}} \right) n_\eta \right] \quad (7.61)$$

and the time discretization for the  $r$ -momentum equation reads:

$$\oint_{\partial\Omega_{\xi\eta}} \left[ (y_\eta (q^{n+\theta,p} + \theta\Delta q) - x_\eta (r^{n+\theta,p} + \theta\Delta r)) \frac{r^{n+\theta,p} + \theta\Delta r}{h^{n+\theta,p} + \theta\Delta h} n_\xi + (-y_\xi (q^{n+\theta,p} + \theta\Delta q) + x_\xi (r^{n+\theta,p} + \theta\Delta r)) \frac{r^{n+\theta,p} + \theta\Delta r}{h^{n+\theta,p} + \theta\Delta h} n_\eta \right] dl \quad (7.62)$$

The linearization in time for the  $r$ -momentum equation reads (see ??):

$$\frac{1}{2} \left[ (y_\eta q^{n+\theta,p} - x_\eta r^{n+\theta,p}) \frac{r^{n+\theta,p}}{h^{n+\theta,p}} n_\xi + (-y_\xi q^{n+\theta,p} + x_\xi r^{n+\theta,p}) \frac{r^{n+\theta,p}}{h^{n+\theta,p}} n_\eta \right] + \quad (7.63)$$

$$+ \frac{1}{2} \theta \Delta h \left[ \left( \frac{-y_\eta q^{n+\theta,p} r^{n+\theta,p} + x_\eta (r^{n+\theta,p})^2}{(h^{n+\theta,p})^2} \right) n_\xi + \left( \frac{y_\xi q^{n+\theta,p} r^{n+\theta,p} - x_\xi (r^{n+\theta,p})^2}{(h^{n+\theta,p})^2} \right) n_\eta \right] + \quad (7.64)$$

$$+ \frac{1}{2} \theta \Delta q \left[ \left( \frac{y_\eta r^{n+\theta,p}}{h^{n+\theta,p}} \right) n_\xi + \left( \frac{-y_\xi r^{n+\theta,p}}{h^{n+\theta,p}} \right) n_\eta \right] \quad (7.65)$$

$$+ \frac{1}{2} \theta \Delta r \left[ \left( \frac{y_\eta q^{n+\theta,p} - 2x_\eta r^{n+\theta,p}}{h^{n+\theta,p}} \right) n_\xi + \left( \frac{-y_\xi q^{n+\theta,p} + 2x_\xi r^{n+\theta,p}}{h^{n+\theta,p}} \right) n_\eta \right] + \quad (7.66)$$

#### 7.1.2.4 Bed shear stress

The bed shear stress term in vector notation reads:

$$J \int_{\Omega_{\xi\eta}} c_f \left( \frac{\mathbf{q} |\mathbf{q}|}{h^2} \right) d\xi d\eta. \quad (7.67)$$

The components for the two momentum equations read:

$$F_q = J \int_{\Omega_{\xi\eta}} c_f \left( \frac{q |\mathbf{q}|}{h^2} \right) d\xi d\eta, \quad q\text{-momentum eq.} \quad (7.68)$$

$$F_r = J \int_{\Omega_{\xi\eta}} c_f \left( \frac{r |\mathbf{q}|}{h^2} \right) d\xi d\eta, \quad r\text{-momentum eq.} \quad (7.69)$$

and  $|\mathbf{q}| = \sqrt{q^2 + r^2}$ . To avoid the discontinuity in the first derivative around zero, the absolute function will be approximated by (the Newton iteration process needs  $C^1$ -continuous functions)

$$|\mathbf{q}| \approx |\tilde{\mathbf{q}}| = ((q^2 + r^2)^2 + \varepsilon^4)^{\frac{1}{4}}. \quad (7.70)$$

The bed shear stress then reads:

$$F_q \approx J c_f \left( \frac{q |\tilde{\mathbf{q}}|}{h^2} \right), \quad q\text{-momentum eq.} \quad (7.71)$$

$$F_r \approx J c_f \left( \frac{r |\tilde{\mathbf{q}}|}{h^2} \right), \quad r\text{-momentum eq.} \quad (7.72)$$

The Jacobian for the bed shear stress  $F(h, q, r)$  reads:

$$\begin{pmatrix} \frac{\partial F_q}{\partial h} & \frac{\partial F_q}{\partial q} & \frac{\partial F_q}{\partial r} \\ \frac{\partial F_r}{\partial h} & \frac{\partial F_r}{\partial q} & \frac{\partial F_r}{\partial r} \end{pmatrix} = \quad (7.73)$$

$$= \begin{pmatrix} -2c_f \frac{q|\tilde{\mathbf{q}}|}{h^3} & c_f \frac{|\tilde{\mathbf{q}}|}{h^2} + c_f \frac{q(q^2+r^2)}{h^2 |\tilde{\mathbf{q}}|^3} & c_f \frac{q}{h^2} \frac{r(q^2+r^2)}{|\tilde{\mathbf{q}}|^3} \\ -2c_f \frac{r|\tilde{\mathbf{q}}|}{h^3} & c_f \frac{r}{h^2} \frac{q(q^2+r^2)}{|\tilde{\mathbf{q}}|^3} & c_f \frac{r}{h^2} \frac{r(q^2+r^2)}{|\tilde{\mathbf{q}}|^3} \end{pmatrix} \quad (7.74)$$

All these coefficients of the Jacobian should be evaluated at the quadrature point of the sub-control volumes and evaluated at time level  $(n + \theta, p)$ . The same applies also for the right hand side and evaluated at time level  $(n + \theta, p)$ .

The linearization in time for the  $q$ -momentum equation reads (see equation (3.42)):

$$J c_f \left( \frac{q_{qp}^{n+\theta,p} \widetilde{|\mathbf{q}_{qp}^{n+\theta,p}|}}{(h_{qp}^{n+\theta,p})^2} \right) - J \left( 2c_f \frac{q_{qp}^{n+\theta,p} \widetilde{|\mathbf{q}_{qp}^{n+\theta,p}|}}{(h_{qp}^{n+\theta,p})^3} \right) \theta \Delta h_{qp} + \quad (7.75)$$

$$+ J \left( c_f \frac{\widetilde{|\mathbf{q}_{qp}^{n+\theta,p}|}}{(h_{qp}^{n+\theta,p})^2} + c_f \frac{q_{qp}^{n+\theta,p}}{(h_{qp}^{n+\theta,p})^2} \frac{q_{qp}^{n+\theta,p} ((q_{qp}^{n+\theta,p})^2 + (r_{qp}^{n+\theta,p})^2)}{|\widetilde{\mathbf{q}_{qp}^{n+\theta,p}}|^3} \right) \theta \Delta q_{qp} + \quad (7.76)$$

$$+ J \left( c_f \frac{q_{qp}^{n+\theta,p}}{(h_{qp}^{n+\theta,p})^2} \frac{r_{qp}^{n+\theta,p} ((q_{qp}^{n+\theta,p})^2 + (r_{qp}^{n+\theta,p})^2)}{|\widetilde{\mathbf{q}_{qp}^{n+\theta,p}}|^3} \right) \theta \Delta r_{qp} \quad (7.77)$$

and for the  $r$ -momentum equation:

$$J c_f \left( \frac{r_{qp}^{n+\theta,p} \widetilde{|\mathbf{q}_{qp}^{n+\theta,p}|}}{(h_{qp}^{n+\theta,p})^2} \right) - J \left( 2c_f \frac{r_{qp}^{n+\theta,p} \widetilde{|\mathbf{q}_{qp}^{n+\theta,p}|}}{(h_{qp}^{n+\theta,p})^3} \right) \theta \Delta h_{qp} + \quad (7.78)$$

$$+ \left( J c_f \frac{r_{qp}^{n+\theta,p}}{(h_{qp}^{n+\theta,p})^2} \frac{q_{qp}^{n+\theta,p} ((q_{qp}^{n+\theta,p})^2 + (r_{qp}^{n+\theta,p})^2)}{|\widetilde{\mathbf{q}_{qp}^{n+\theta,p}}|^3} \right) \theta \Delta q_{qp} + \quad (7.79)$$

$$+ J \left( c_f \frac{\widetilde{|\mathbf{q}_{qp}^{n+\theta,p}|}}{(h_{qp}^{n+\theta,p})^2} + c_f \frac{r_{qp}^{n+\theta,p}}{(h_{qp}^{n+\theta,p})^2} \frac{r_{qp}^{n+\theta,p} ((q_{qp}^{n+\theta,p})^2 + (r_{qp}^{n+\theta,p})^2)}{|\widetilde{\mathbf{q}_{qp}^{n+\theta,p}}|^3} \right) \theta \Delta r_{qp} \quad (7.80)$$

with

$$\left| \widetilde{\mathbf{q}}_{qp}^{n+\theta,p} \right| = ((q_{qp}^2 + r_{qp}^2)^2 + \varepsilon^4)^{\frac{1}{4}}. \quad (7.81)$$

These terms need to be computed for each quadrature points ( $qp$ ) of the sub-control volumes.

### 7.1.2.5 Viscosity

The viscosity term in vector notation reads:

$$- \int_{\Omega} \nabla \cdot (\nu h (\nabla(\mathbf{q}/h) + \nabla(\mathbf{q}^T/h))) d\omega \quad (7.82)$$

For the  $x$ -momentum equation the viscous terms can be transformed as (see [equation \(A.46\)](#)):

$$-\frac{\partial}{\partial x} \left( 2\nu h \frac{\partial(q/h)}{\partial x} \right) - \frac{\partial}{\partial y} \left( \nu h \frac{\partial(r/h)}{\partial x} + \nu h \frac{\partial(q/h)}{\partial y} \right) = \quad (7.83)$$

$$= -\frac{1}{J} \frac{\partial}{\partial \xi} \left[ \frac{\nu h}{J} \left( -x_{\eta} \frac{\partial}{\partial \xi} \left( x_{\eta} \frac{q}{h} + y_{\eta} \frac{r}{h} \right) + x_{\eta} \frac{\partial}{\partial \eta} \left( x_{\xi} \frac{q}{h} + y_{\xi} \frac{r}{h} \right) + \right. \right. \quad (7.84)$$

$$\left. \left. + 2y_{\eta} \frac{\partial(y_{\eta} q/h)}{\partial \xi} - 2y_{\eta} \frac{\partial(y_{\xi} q/h)}{\partial \eta} \right] \right. \quad (7.85)$$

$$+ \frac{1}{J} \frac{\partial}{\partial \eta} \left[ \frac{\nu h}{J} \left( -x_{\xi} \frac{\partial}{\partial \xi} \left( x_{\eta} \frac{q}{h} + y_{\eta} \frac{r}{h} \right) + x_{\xi} \frac{\partial}{\partial \eta} \left( x_{\xi} \frac{q}{h} + y_{\xi} \frac{r}{h} \right) + \right. \right. \quad (7.86)$$

$$\left. \left. + 2y_{\xi} \frac{\partial(y_{\eta} q/h)}{\partial \xi} - 2y_{\xi} \frac{\partial(y_{\xi} q/h)}{\partial \eta} \right] \right. \quad (7.87)$$

$$(7.88)$$

and for the  $y$ -momentum equation the viscous terms can be transformed as (see [equation \(A.51\)](#)):

$$-\frac{\partial}{\partial x} \left( \nu h \frac{\partial(r/h)}{\partial x} + \nu h \frac{\partial(q/h)}{\partial y} \right) - \frac{\partial}{\partial y} \left( 2\nu h \frac{\partial(r/h)}{\partial y} \right) = \quad (7.89)$$

$$= -\frac{1}{J} \frac{\partial}{\partial \xi} \left[ \frac{\nu h}{J} \left( y_{\eta} \frac{\partial}{\partial \xi} \left( y_{\eta} \frac{r}{h} + x_{\eta} \frac{q}{h} \right) - y_{\eta} \frac{\partial}{\partial \eta} \left( y_{\xi} \frac{r}{h} + x_{\xi} \frac{q}{h} \right) + \right. \right. \quad (7.90)$$

$$\left. \left. + 2x_{\eta} \frac{\partial(x_{\eta} r/h)}{\partial \xi} - 2x_{\eta} \frac{\partial(x_{\xi} r/h)}{\partial \eta} \right) \right]. \quad (7.91)$$

$$+ \frac{1}{J} \frac{\partial}{\partial \eta} \left[ \frac{\nu h}{J} \left( y_{\xi} \frac{\partial}{\partial \xi} \left( y_{\eta} \frac{r}{h} + x_{\eta} \frac{q}{h} \right) - y_{\xi} \frac{\partial}{\partial \eta} \left( y_{\xi} \frac{r}{h} + x_{\xi} \frac{q}{h} \right) + \right. \right. \quad (7.92)$$

$$\left. \left. + 2x_{\xi} \frac{\partial(x_{\eta} r/h)}{\partial \xi} - 2x_{\xi} \frac{\partial(x_{\xi} r/h)}{\partial \eta} \right) \right]. \quad (7.93)$$

This terms need to be computed for each of the control volume faces, taken into account the outward normal. Eight faces on a cartesian/curvilinear grid.

### For a cartesian grid

The viscosity term on a cartesian grid, after applying Green's theorem with  $\mathbf{n} = (n_\xi, n_\eta)^T$  the outward normal vector, reads for the  $x$ -momentum equation:

$$\begin{aligned} & - \left[ \frac{\nu h}{J} \left( 2y_\eta \frac{\partial}{\partial \xi} \left( y_\eta \frac{q}{h} \right) \right) \right] n_\xi + \\ & + \left[ \frac{\nu h}{J} \left( -x_\xi \frac{\partial}{\partial \xi} \left( y_\eta \frac{r}{h} \right) + x_\xi \frac{\partial}{\partial \eta} \left( x_\xi \frac{q}{h} \right) \right) \right] n_\eta \end{aligned} \quad (7.94)$$

Written in linear terms for the derivatives it reads:

$$- \left[ \frac{\nu}{J} \left( 2y_\eta y_{\xi\eta} q + 2y_\eta y_\eta \left( \frac{\partial q}{\partial \xi} - \frac{q}{h} \frac{\partial h}{\partial \xi} \right) \right) \right] n_\xi + \quad (7.95)$$

$$+ \left[ \frac{\nu}{J} \left( -x_\xi y_{\xi\eta} r - x_\xi y_\eta \left( \frac{\partial r}{\partial \xi} - \frac{r}{h} \frac{\partial h}{\partial \xi} \right) + x_\xi x_{\eta\xi} q + x_\xi x_\xi \left( \frac{\partial q}{\partial \eta} - \frac{q}{h} \frac{\partial h}{\partial \eta} \right) \right) \right] n_\eta \quad (7.96)$$

and for the  $y$ -momentum to:

$$\begin{aligned} & - \left[ \frac{\nu h}{J} \left( y_\eta \frac{\partial}{\partial \xi} \left( y_\eta \frac{r}{h} \right) - y_\eta \frac{\partial}{\partial \eta} \left( x_\xi \frac{q}{h} \right) \right) \right] n_\xi + \\ & + \left[ \frac{\nu h}{J} \left( -2x_\xi \frac{\partial}{\partial \eta} \left( x_\xi \frac{r}{h} \right) \right) \right] n_\eta. \end{aligned} \quad (7.97)$$

Written in linear terms for the derivatives it reads:

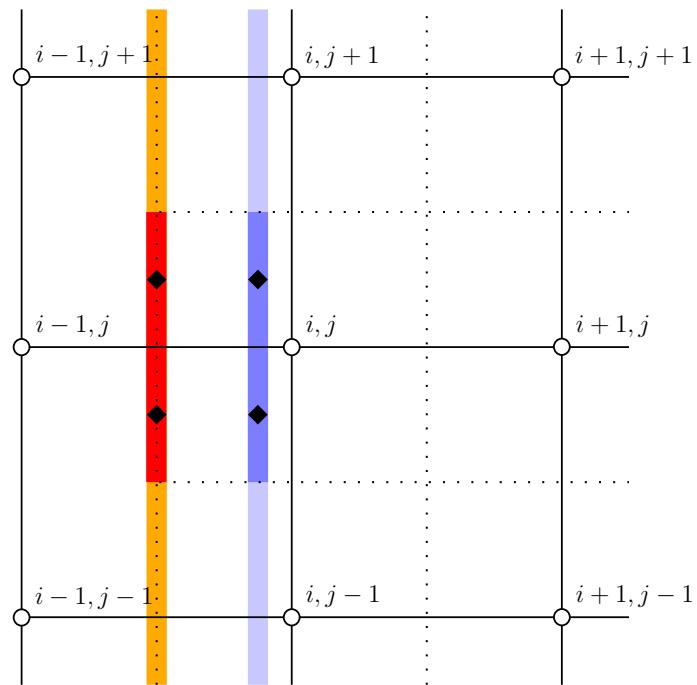
$$\begin{aligned} & - \left[ \frac{\nu}{J} \left( y_\eta y_{\xi\eta} r + y_\eta y_\eta \left( \frac{\partial r}{\partial \xi} - \frac{r}{h} \frac{\partial h}{\partial \xi} \right) - y_\eta x_{\eta\xi} q - y_\eta x_\xi \left( \frac{\partial q}{\partial \eta} - \frac{q}{h} \frac{\partial h}{\partial \eta} \right) \right) \right] n_\xi + \\ & + \left[ \frac{\nu h}{J} \left( -2x_\xi x_{\eta\xi} r - 2x_\xi x_\xi \left( \frac{\partial r}{\partial \eta} - \frac{r}{h} \frac{\partial h}{\partial \eta} \right) \right) \right] n_\eta. \end{aligned} \quad (7.98)$$

### 7.1.3 Discretization at boundary

For the 2D non-linear wave equations (equation (7.5)) at each boundary boundary conditions need to be prescribed, the number of boundary conditions depends on the flow direction on the boundary. Considering a hyperbolic system, if the flow is flowing into the domain two boundary conditions need to be prescribed and when the flow is flowing out the domain just one boundary need to be prescribed. This is according the characteristic theory of 2D hyperbolic systems

(Daubert and Graffe, 1967). The ingoing information is called the **essential** boundary condition (Dirichlet or Neumann condition). And a boundary condition to handle the outgoing wave is called the **natural** boundary condition. So for inflow there are **two essential** and **one natural** boundary condition and for outflow there is **one essential** boundary condition and **two natural** boundary conditions.

The natural boundary condition is always located at the boundary of a control volume and the essential (the genuine) boundary condition is always located inside the last control volume of the grid, as indicated in [Figure 7.3](#).

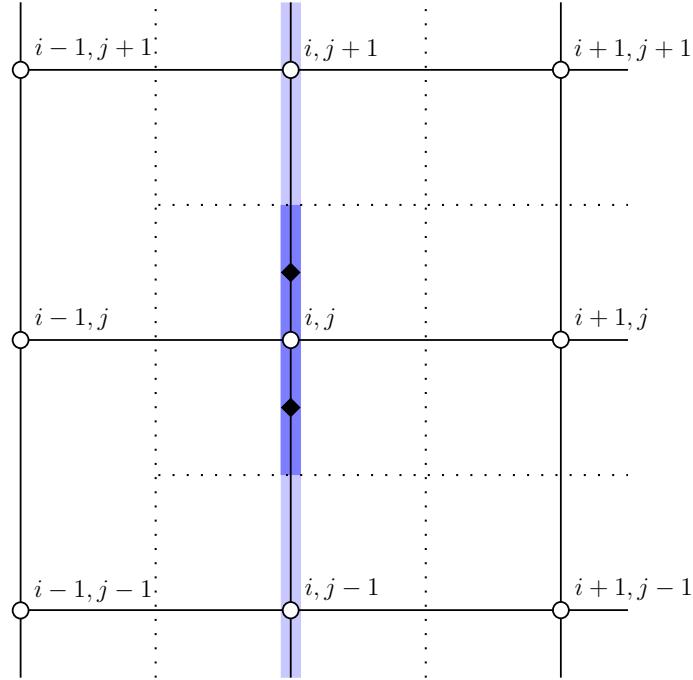


**Figure 7.3:** Dotted lines indicate the border of the control volumes. The natural boundary condition is located at the boundary of a control volume, the orange line and the essential boundary condition is located inside the last control volume, the cyan-colored line. The black diamonds are the location of the quadrature points at the boundary.

The boundary conditions in this section are presented for the left/west boundary. First the **essential** boundary conditions are discussed and after that the **natural** boundary condition. A similar derivation can be given for right/east boundary.

### 7.1.3.1 Essential boundary condition

The **essential** boundary condition is to be assumed somewhere in the first control volume, ( $x_{i_{bc}}$  with  $i_{bc} \in [i - \frac{1}{2}, i + \frac{1}{2}]$ ). For simplicity the boundary condition is chosen to be on node  $i = 1$  (location  $x_1$ ).



**Figure 7.4:** Essential boundary condition, dotted lines indicate the border of the control volumes.

The **essential** boundary condition for the left/west boundary at  $x_1$  reads, describing the ingoing wave (indicated with  $h^+$ ,  $q^+$ ,  $r^+$ ) with as less as possible disturbing the outgoing wave (equation (5.59)):

$$\left(\sqrt{gh} - \frac{q}{h}\right) \frac{\partial h^+}{\partial t} + \frac{\partial q^+}{\partial t} = F(t) \quad (7.99)$$

$$\left(\sqrt{gh} + \frac{q}{h}\right) \frac{\partial h^+}{\partial t} - \frac{\partial q^+}{\partial t} = 0 \quad (7.100)$$

Equation (7.100) means that the ingoing wave does not disturb the outgoing wave. And we assume normal incoming waves, which means that  $r^+ = 0$ .

The **essential** boundary condition for the right/east boundary at  $x_{I+\frac{1}{2}}$  reads, describing the ingoing wave (indicated with  $h^-$ ,  $q^-$ ,  $r^-$ ) with as less as possible disturbing the outgoing wave (equation (5.59)):

$$\left(\sqrt{gh} + \frac{q}{h}\right) \frac{\partial h^-}{\partial t} - \frac{\partial q^-}{\partial t} = G(t) \quad (7.101)$$

$$\left(\sqrt{gh} - \frac{q}{h}\right) \frac{\partial h^-}{\partial t} + \frac{\partial q^-}{\partial t} = 0 \quad (7.102)$$

**Equation (7.102)** means that the ingoing wave does not disturb the outgoing wave.

### *Given water level at left / west boundary*

Adding the equations ((7.99) + (7.100)) yields

$$2\sqrt{gh}\frac{\partial h}{\partial t} = F(t) \quad (7.103)$$

So the essential boundary condition for incoming signal (if  $\partial z_b/\partial t = 0$ ) reads

$$\left(\sqrt{gh} - \frac{q}{h}\right)\frac{\partial h^+}{\partial t} + \frac{\partial q^+}{\partial t} = 2\sqrt{gh}\frac{\partial \zeta_{given}}{\partial t} + \varepsilon(\zeta_{given} - \zeta) \quad (7.104)$$

a correction term is added, to prevent drifting away of the solution (an integration constant is missing). The variable  $\varepsilon$  has dimension [ $\text{m s}^{-2}$ ].

The discretization of boundary equation (7.112) at  $x = i + \frac{1}{2}$  reads (when  $\partial z_b/\partial t = 0$ ):

$$\begin{aligned} & \left(\sqrt{gh^{n+\theta,p+1}} - \frac{q^{n+\theta,p+1}}{h^{n+\theta,p+1}}\right)\frac{\partial h^+}{\partial t} + \frac{\partial q^+}{\partial t} = \\ & = 2\sqrt{gh^{n+\theta,p+1}}\frac{\partial \zeta_{given}}{\partial t} + \varepsilon((\zeta_{given} - z_b) - h^{n+1,p}) \end{aligned} \quad (7.105)$$

### *Given water flux at left / west boundary*

Subtracting the equations ((7.99) – (7.100)), yields:

$$-2\frac{q}{h}\frac{\partial h}{\partial t} + 2\frac{\partial q}{\partial t} = F(h, q, t) \quad (7.106)$$

So the essential boundary condition for incoming signal reads

$$\left(\sqrt{gh} - \frac{q}{h}\right)\frac{\partial h^+}{\partial t} + \frac{\partial q^+}{\partial t} = -2\frac{q}{h}\frac{\partial h}{\partial t} + 2\frac{\partial q}{\partial t} \quad (7.107)$$

Using equation (7.100) (ingoing information does not disturb outgoing information)

$$\left(\sqrt{gh} + \frac{q}{h}\right)\frac{\partial h^+}{\partial t} - \frac{\partial q^+}{\partial t} = 0 \Rightarrow \frac{\partial h^+}{\partial t} = \frac{1}{\sqrt{gh} + \frac{q}{h}}\frac{\partial q^+}{\partial t} \quad (7.108)$$

substituting equation (7.108) into the right hand side of equation (7.107), yields

$$\left(\sqrt{gh} - \frac{q}{h}\right)\frac{\partial h^+}{\partial t} + \frac{\partial q^+}{\partial t} = 2\left(\frac{\sqrt{gh}}{\sqrt{gh} + \frac{q}{h}}\right)\frac{\partial q_{given}}{\partial t} + \varepsilon(q_{given} - q) \quad (7.109)$$

a correction term is added, to prevent drifting away of the solution (an integration constant is missing). The variable  $\varepsilon$  has dimension [ $\text{s}^{-1}$ ]. The discretization

of boundary equation (7.109) at  $x = i + \frac{1}{2}$  reads

$$\begin{aligned} & \left( \sqrt{gh^{n+\theta,p+1}} - \frac{q^{n+\theta,p+1}}{h^{n+\theta,p+1}} \right) \frac{\partial h}{\partial t} + \frac{\partial q}{\partial t} = \\ & = 2 \left( \frac{\sqrt{gh^{n+\theta,p+1}}}{\sqrt{gh^{n+\theta,p+1}} + \frac{q^{n+\theta,p+1}}{h^{n+\theta,p+1}}} \right) \frac{\partial q_{given}}{\partial t} + \varepsilon (q_{given} - q^{n+1,p}) \end{aligned} \quad (7.110)$$

*Given water level at left/west boundary*

Adding the equations ((5.101) + (5.102)) yields

$$2\sqrt{gh} \frac{\partial h}{\partial t} = F(t) \quad (7.111)$$

So the essential boundary condition for incoming signal (if  $\partial z_b / \partial t = 0$ ) reads

$$\boxed{\left( \sqrt{gh} - \frac{q}{h} \right) \frac{\partial h^+}{\partial t} + \frac{\partial q^+}{\partial t} = 2\sqrt{gh} \frac{\partial \zeta_{given}}{\partial t} + \varepsilon (\zeta_{given} - \zeta)} \quad (7.112)$$

a correction term is added, to prevent drifting away of the solution (an integration constant is missing). The variable  $\varepsilon$  has dimension [ $\text{m s}^{-2}$ ].

The discretization of boundary equation (7.112) at  $x = i + \frac{1}{2}$  reads

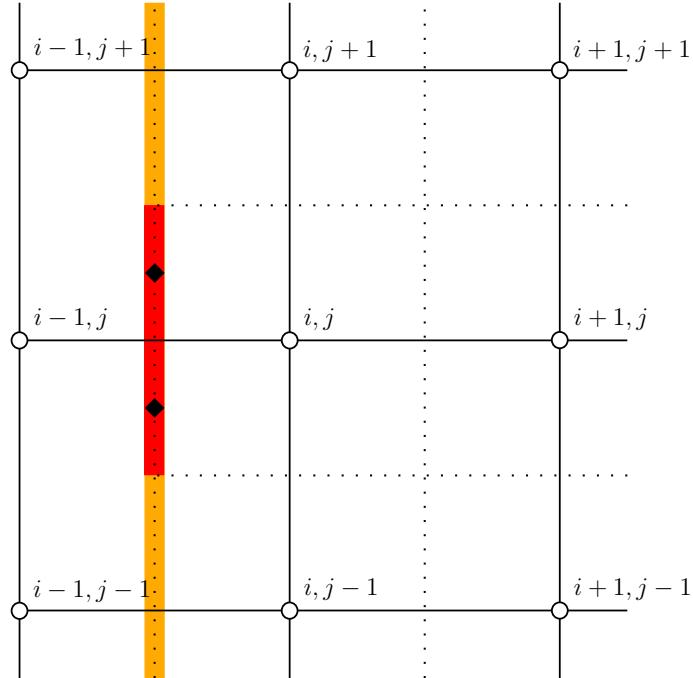
$$\begin{aligned} & \left( \sqrt{gh^{n+\theta,p+1}} - \frac{q^{n+\theta,p+1}}{h^{n+\theta,p+1}} \right) \frac{\partial h^+}{\partial t} + \frac{\partial q^+}{\partial t} = \\ & = 2\sqrt{gh^{n+\theta,p+1}} \frac{\partial \zeta_{given}}{\partial t} + \varepsilon ((\zeta_{given} - z_b) - h^{n+1,p}) \end{aligned} \quad (7.113)$$

### 7.1.3.2 Natural boundary condition

The **natural** boundary condition for the left/west boundary, describing the undisturbed outgoing wave, reads (equation (5.59)):

$$-\left(\sqrt{gh} + \frac{q}{h}\right) \underbrace{\left(\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} + \dots\right)}_{\text{continuity eq.}} + \underbrace{\left(\frac{\partial q}{\partial t} + gh \frac{\partial \zeta}{\partial x} + \dots\right)}_{\text{momentum eq.}} = 0 \quad (7.114)$$

where  $q$  is normal to this boundary.



**Figure 7.5:** Natural boundary condition ( $i = 1$ ), dotted lines indicate the border of the control volumes. The diamonds indicate the quadrature points.

#### Time derivative, continuity equation

At the left/west boundary ( $x_{i-\frac{1}{2},j-\frac{1}{4}}$  with  $i = 1$ ) the time discretization of the continuity equation for the **natural** boundary condition, describing the outgoing wave, reads:

$$\int_{\Gamma} \frac{\partial h}{\partial t} ds \Big|_{i-\frac{1}{2},j-\frac{1}{4}} \approx \frac{1}{2} \frac{y_{\eta}}{\Delta t} \left( h_{i-\frac{1}{2},j-\frac{1}{4}}^{n+1} - h_{i-\frac{1}{2},j-\frac{1}{4}}^n \right) \quad (7.115)$$

with  $y_{\eta}$  defined at  $(i - \frac{1}{2}, j - \frac{1}{4})$ .

A diffusion like term is added to the boundary equation to damp the reflection of spurious waves. A coefficient  $\alpha_{bnd}$  is placed before that extra term, the optimal

value of this coefficient is taken from the analysis in [Borsboom \(2009\)](#).

$$\begin{aligned} \frac{1}{2} \frac{y_\eta}{\Delta t} & \left[ \frac{1}{2} \left( h_{i-1,j-\frac{1}{4}}^{n+1,p+1} + h_{i,j-\frac{1}{4}}^{n+1,p+1} \right) + \frac{\alpha_{bnd}}{2} \left( h_{i-1,j-\frac{1}{4}}^{n+1,p+1} - 2h_{i,j-\frac{1}{4}}^{n+1,p+1} + h_{i+1,j-\frac{1}{4}}^{n+1,p+1} \right) + \right. \\ & \left. - \left( \frac{1}{2} \left( h_{i-1,j-\frac{1}{4}}^n + h_{i,j-\frac{1}{4}}^n \right) + \frac{\alpha_{bnd}}{2} \left( h_{i-1,j-\frac{1}{4}}^n - 2h_{i,j-\frac{1}{4}}^n + h_{i+1,j-\frac{1}{4}}^n \right) \right) \right] \end{aligned} \quad (7.116)$$

After rearranging the equation to the  $\Delta$ -formulation, the implicit and the explicit part reads:

$$\begin{aligned} \frac{1}{2} \frac{y_\eta}{\Delta t} & \left( \frac{1}{2} \left( \Delta h_{i-1,j-\frac{1}{4}}^{n+1,p+1} + \Delta h_{i,j-\frac{1}{4}}^{n+1,p+1} \right) + \right. \\ & + \frac{\alpha_{bnd}}{2} \left( \Delta h_{i-1,j-\frac{1}{4}}^{n+1,p+1} - 2\Delta h_{i,j-\frac{1}{4}}^{n+1,p+1} + \Delta h_{i+1,j-\frac{1}{4}}^{n+1,p+1} \right) + \\ & + \frac{1}{2} \frac{y_\eta}{\Delta t} \left\{ \frac{1}{2} \left( h_{i-1,j-\frac{1}{4}}^{n+1,p} + h_{i,j-\frac{1}{4}}^{n+1,p} \right) + \frac{\alpha_{bnd}}{2} \left( h_{i-1,j-\frac{1}{4}}^{n+1,p} - 2h_{i,j-\frac{1}{4}}^{n+1,p} + h_{i+1,j-\frac{1}{4}}^{n+1,p} \right) + \right. \\ & \left. - \left( \frac{1}{2} \left( h_{i-1,j-\frac{1}{4}}^n + h_{i,j-\frac{1}{4}}^n \right) + \frac{\alpha_{bnd}}{2} \left( h_{i-1,j-\frac{1}{4}}^n - 2h_{i,j-\frac{1}{4}}^n + h_{i+1,j-\frac{1}{4}}^n \right) \right) \right\} \end{aligned} \quad (7.117)$$

### *Mass flux, continuity equation*

At the left/west boundary ( $x_{i-\frac{1}{2},j-\frac{1}{4}}$  with  $i = 1$ ) the discretization of the mass flux for the **natural** boundary condition reads, describing the outgoing wave (assuming  $\partial r / \partial y = 0$  and already multiplied by  $J$ ):

$$\int_{\Gamma} \frac{\partial q}{\partial x} ds = \int_{\Gamma} \left( y_\eta \frac{\partial q}{\partial \xi} - y_\xi \frac{\partial q}{\partial \eta} \right) ds \quad (7.118)$$

which will be approximated by ( $\Delta \xi = \Delta \eta = 1$ ):

$$\frac{1}{2} y_\eta \left( \left( q_{i,j-\frac{1}{4}}^{n+\theta,p} + \theta \Delta q_{i,j-\frac{1}{4}}^{n+1,p+1} \right) - \left( q_{i-1,j-\frac{1}{4}}^{n+\theta,p+1} + \theta \Delta q_{i-1,j-\frac{1}{4}}^{n+1,p+1} \right) \right) \quad (7.119)$$

$$\Leftrightarrow \quad (7.120)$$

$$\frac{1}{2} y_\eta \theta \left( \Delta q_{i,j-\frac{1}{4}}^{n+1,p+1} - \Delta q_{i-1,j-\frac{1}{4}}^{n+1,p+1} \right) + y_\eta \left\{ q_{i,j-\frac{1}{4}}^{n+\theta,p} - q_{i-1,j-\frac{1}{4}}^{n+\theta,p+1} \right\} \quad (7.121)$$

### *Time derivative, momentum equation*

At the left/west boundary ( $x_{i-\frac{1}{2},j-\frac{1}{4}}$  with  $i = 1$ ) the time discretization of the momentum equation for the **natural** boundary condition, describing the outgoing wave, reads:

$$\int_{\Gamma} \frac{\partial q}{\partial t} ds \Big|_{i-\frac{1}{2},j-\frac{1}{4}} \approx \frac{1}{2} \frac{y_\eta}{\Delta t} \left( q_{i-\frac{1}{2},j-\frac{1}{4}}^{n+1} - q_{i-\frac{1}{2},j-\frac{1}{4}}^n \right) \quad (7.122)$$

A diffusion like term is added to the boundary equation to damp the reflection of spurious waves. A coefficient  $\alpha_{bnd}$  is placed before that extra term, the optimal

value of this coefficient is taken from the analysis in [Borsboom \(2009\)](#).

$$\begin{aligned} \frac{1}{2} \frac{y_\eta}{\Delta t} & \left[ \frac{1}{2} \left( q_{i-1,j-\frac{1}{4}}^{n+1,p+1} + q_{i,j-\frac{1}{4}}^{n+1,p+1} \right) + \frac{\alpha_{bnd}}{2} \left( q_{i-1,j-\frac{1}{4}}^{n+1,p+1} - 2q_{i,j-\frac{1}{4}}^{n+1,p+1} + q_{i+1,j-\frac{1}{4}}^{n+1,p+1} \right) + \right. \\ & \left. - \left( \frac{1}{2} \left( q_{i-1,j-\frac{1}{4}}^n + q_{i,j-\frac{1}{4}}^n \right) + \frac{\alpha_{bnd}}{2} \left( q_{i-1,j-\frac{1}{4}}^n - 2q_{i,j-\frac{1}{4}}^n + q_{i+1,j-\frac{1}{4}}^n \right) \right) \right] \end{aligned} \quad (7.123)$$

After rearranging the equation to the  $\Delta$ -formulation, the implicit and the explicit part reads:

$$\begin{aligned} \frac{1}{2} \frac{y_\eta}{\Delta t} & \left( \frac{1}{2} \left( \Delta q_{i-1,j-\frac{1}{4}}^{n+1,p+1} + \Delta q_{i,j-\frac{1}{4}}^{n+1,p+1} \right) + \right. \\ & \left. + \frac{\alpha_{bnd}}{2} \left( \Delta q_{i-1,j-\frac{1}{4}}^{n+1,p+1} - 2\Delta q_{i,j-\frac{1}{4}}^{n+1,p+1} + \Delta q_{i+1,j-\frac{1}{4}}^{n+1,p+1} \right) \right) + \\ & + \frac{1}{2} \frac{y_\eta}{\Delta t} \left\{ \frac{1}{2} \left( q_{i-1,j-\frac{1}{4}}^{n+1,p} + q_{i,j-\frac{1}{4}}^{n+1,p} \right) + \frac{\alpha_{bnd}}{2} \left( q_{i-1,j-\frac{1}{4}}^{n+1,p} - 2q_{i,j-\frac{1}{4}}^{n+1,p} + q_{i+1,j-\frac{1}{4}}^{n+1,p} \right) + \right. \\ & \left. - \frac{1}{2} \left( q_{i-1,j-\frac{1}{4}}^n + q_{i,j-\frac{1}{4}}^n \right) - \frac{\alpha_{bnd}}{2} \left( q_{i-1,j-\frac{1}{4}}^n - 2q_{i,j-\frac{1}{4}}^n + q_{i+1,j-\frac{1}{4}}^n \right) \right\} \end{aligned} \quad (7.124)$$

### *Pressure term, momentum equation*

At the left/west boundary ( $x_{i-\frac{1}{2},j-\frac{1}{4}}$  with  $i = 1$ ) the discretization of the pressure term for the **natural** boundary condition, describing the outgoing wave, reads:

$$\int_{\Gamma} \left( gh \frac{\partial \zeta}{\partial x} \right) ds \Big|_{i-\frac{1}{2},j-\frac{1}{4}} \approx \frac{1}{2} gh \left( y_\eta \frac{\partial \zeta}{\partial \xi} - y_\xi \frac{\partial \zeta}{\partial \eta} \right) \quad (7.125)$$

In a formulation of the shallow-water equations, where the bed level is time independent it can be used that  $\Delta \zeta = \Delta h$ . In that case, the contributions to  $\Delta \zeta$  need to be incorporated to  $\Delta h$ . The pressure term will then be approximated by (assuming  $y_\xi = 0$ )

$$\begin{aligned} \frac{1}{2} y_\eta g h_{i-\frac{1}{2},j-\frac{1}{4}}^{n+\theta,p} & \left( \zeta_{i,j-\frac{1}{4}}^{n+\theta,p} - \zeta_{i-1,j-\frac{1}{4}}^{n+\theta,p} \right) + \\ & + \frac{1}{2} y_\eta g \left( \zeta_{i,j-\frac{1}{4}}^{n+\theta,p} - \zeta_{i-1,j-\frac{1}{4}}^{n+\theta,p} \right) \theta \Delta h_{i-\frac{1}{2},j-\frac{1}{4}}^{n+1,p+1} + \\ & + \frac{1}{2} y_\eta g h_{i-\frac{1}{2},j-\frac{1}{4}}^{n+\theta,p} \theta \left( \Delta \zeta_{i,j-\frac{1}{4}}^{n+1,p+1} - \Delta \zeta_{i-1,j-\frac{1}{4}}^{n+1,p+1} \right) \end{aligned} \quad (7.126)$$

After rearranging the equation into an implicit and an explicit part it reads:

$$\frac{1}{2} y_\eta g \left( \zeta_{i,j-\frac{1}{4}}^{n+\theta,p} - \zeta_{i-1,j-\frac{1}{4}}^{n+\theta,p} \right) \theta \Delta h_{i-\frac{1}{2},j-\frac{1}{4}}^{n+1,p+1} + \quad (7.127)$$

$$\begin{aligned} & + \frac{1}{2} y_\eta g h_{i-\frac{1}{2},j-\frac{1}{4}}^{n+\theta,p} \theta \left( \Delta \zeta_{i,j-\frac{1}{4}}^{n+1,p+1} - \Delta \zeta_{i-1,j-\frac{1}{4}}^{n+1,p+1} \right) + \\ & + \left\{ \frac{1}{2} y_\eta g h_{i-\frac{1}{2},j-\frac{1}{4}}^{n+\theta,p} \left( \zeta_{i,j-\frac{1}{4}}^{n+\theta,p} - \zeta_{i-1,j-\frac{1}{4}}^{n+\theta,p} \right) \right\} \end{aligned} \quad (7.128)$$

### Convection, momentum equation

The finite volume flux through the boundary line element  $ds$  yields

$$\int_{\Gamma} \left( \nabla \cdot \frac{\mathbf{q}\mathbf{q}^T}{h} \right) ds = \int_{\Gamma} \left( \frac{\partial qq/h}{\partial x} + \frac{\partial rq/h}{\partial y} \right) \cdot \mathbf{n} ds = \quad (7.129)$$

$$= \left[ \left( \frac{\partial qq/h}{\partial x} + \frac{\partial rq/h}{\partial y} \right) n_x + \left( \frac{\partial qr/h}{\partial x} + \frac{\partial rr/h}{\partial y} \right) n_y \right] \|ds\| \quad (7.130)$$

with  $\mathbf{n} = (n_x, n_y)^T$  the outward normal vector.

Written in linear terms for the derivative they read:

$$\frac{\partial(qq/h)}{\partial x} = \frac{2q}{h} \frac{\partial q}{\partial x} - \frac{q^2}{h^2} \frac{\partial h}{\partial x} \quad (7.131)$$

$$\frac{\partial(rq/h)}{\partial y} = \frac{q}{h} \frac{\partial r}{\partial y} + \frac{r}{h} \frac{\partial q}{\partial y} - \frac{rq}{h^2} \frac{\partial h}{\partial y} \quad (7.132)$$

$$\frac{\partial(qr/h)}{\partial x} = \frac{r}{h} \frac{\partial q}{\partial x} + \frac{q}{h} \frac{\partial r}{\partial x} - \frac{qr}{h^2} \frac{\partial h}{\partial x} \quad (7.133)$$

$$\frac{\partial(rr/h)}{\partial y} = \frac{2r}{h} \frac{\partial q}{\partial y} - \frac{r^2}{h^2} \frac{\partial h}{\partial y} \quad (7.134)$$

Consider on a cartesian grid the boundary at the west/left side of the domain, ranging over the interval  $[\mathbf{x}_{i-\frac{1}{2},j-\frac{1}{2}}, \mathbf{x}_{i-\frac{1}{2},j+\frac{1}{2}}]$ .

$$\int_{\Gamma} \left( \frac{\partial(qq/h)}{\partial x} + \frac{\partial(rq/h)}{\partial y} \right) ds = \quad (7.135)$$

$$\int_{\Gamma} \left( \frac{2q}{h} \frac{\partial q}{\partial x} - \frac{q^2}{h^2} \frac{\partial h}{\partial x} + \frac{q}{h} \frac{\partial r}{\partial y} + \frac{r}{h} \frac{\partial q}{\partial y} - \frac{rq}{h^2} \frac{\partial h}{\partial y} \right) ds \quad (7.136)$$

which read in transformed coordinates

$$\int_{\Gamma_{\xi\eta}} \left[ \frac{2q}{h} \left( y_{\eta} \frac{\partial q}{\partial \xi} - y_{\xi} \frac{\partial q}{\partial \eta} \right) - \frac{q^2}{h^2} \left( y_{\eta} \frac{\partial h}{\partial \xi} - y_{\xi} \frac{\partial h}{\partial \eta} \right) + \right. \quad (7.137)$$

$$\left. + \frac{q}{h} \left( -x_{\eta} \frac{\partial r}{\partial \xi} + x_{\xi} \frac{\partial r}{\partial \eta} \right) + \frac{r}{h} \left( -x_{\eta} \frac{\partial q}{\partial \xi} + x_{\xi} \frac{\partial q}{\partial \eta} \right) - \frac{rq}{h^2} \left( -x_{\eta} \frac{\partial h}{\partial \xi} + x_{\xi} \frac{\partial h}{\partial \eta} \right) \right] ds \quad (7.138)$$

In case we have normal flow at the boundary ( $r = 0$  and  $x_{\eta} \partial r / \partial \xi = 0$ ) this boundary term reduces to:

$$\int_{\Gamma_{\xi\eta}} \left[ \frac{2q}{h} \left( y_{\eta} \frac{\partial q}{\partial \xi} - y_{\xi} \frac{\partial q}{\partial \eta} \right) - \frac{q^2}{h^2} \left( y_{\eta} \frac{\partial h}{\partial \xi} - y_{\xi} \frac{\partial h}{\partial \eta} \right) \right] ds \quad (7.139)$$

which will be approximated at the quadrature point  $qp$  and at time level  $n + \theta, p$  by

$$\underbrace{\frac{1}{2} \left[ \frac{2q}{h} \left( y_\eta \frac{\partial q}{\partial \xi} - y_\xi \frac{\partial q}{\partial \eta} \right) - \frac{q^2}{h^2} \left( y_\eta \frac{\partial h}{\partial \xi} - y_\xi \frac{\partial h}{\partial \eta} \right) \right]}_{\text{to right hand side}} + \quad (7.140)$$

$$+ \frac{1}{2} \theta \Delta h \underbrace{\left[ - \frac{2q}{h^2} \left( y_\eta \frac{\partial q}{\partial \xi} - y_\xi \frac{\partial q}{\partial \eta} \right) + \frac{2q^2}{h^3} \left( y_\eta \frac{\partial h}{\partial \xi} - y_\xi \frac{\partial h}{\partial \eta} \right) \right]}_{\mathcal{A}} + \quad (7.141)$$

$$+ \frac{1}{2} \theta \Delta q \underbrace{\left[ \frac{2}{h} \left( y_\eta \frac{\partial q}{\partial \xi} - y_\xi \frac{\partial q}{\partial \eta} \right) - \frac{2q}{h^2} \left( y_\eta \frac{\partial h}{\partial \xi} - y_\xi \frac{\partial h}{\partial \eta} \right) \right]}_{\mathcal{B}} + \quad (7.142)$$

$$+ \frac{1}{2} \theta \underbrace{\left( -\frac{q^2}{h^2} \right)}_{\mathcal{C}} \left( y_\eta \frac{\partial \Delta h}{\partial \xi} - y_\xi \frac{\partial \Delta h}{\partial \eta} \right) + \frac{1}{2} \theta \underbrace{\frac{2q}{h}}_{\mathcal{D}} \left( y_\eta \frac{\partial \Delta q}{\partial \xi} - y_\xi \frac{\partial \Delta q}{\partial \eta} \right) \quad (7.143)$$

where  $\mathcal{A}$ ,  $\mathcal{B}$ ,  $\mathcal{C}$  and  $\mathcal{D}$  multiplied by  $\frac{1}{2}\theta$  and *the geometrical factors* are the coefficients in the matrix of the  $\Delta$ -formulation.

For the convection term of the  $r$ -momentum equation it reads:

$$\int_{\Gamma_{\xi\eta}} \left[ \frac{r}{h} \left( y_\eta \frac{\partial q}{\partial \xi} - y_\xi \frac{\partial q}{\partial \eta} \right) + \frac{q}{h} \left( y_\eta \frac{\partial r}{\partial \xi} - y_\xi \frac{\partial r}{\partial \eta} \right) - \frac{qr}{h^2} \left( y_\eta \frac{\partial h}{\partial \xi} - y_\xi \frac{\partial h}{\partial \eta} \right) + \right. \quad (7.144)$$

$$\left. + \frac{2r}{h} \left( -x_\eta \frac{\partial r}{\partial \xi} + x_\xi \frac{\partial r}{\partial \eta} \right) - \frac{r^2}{h^2} \left( -x_\eta \frac{\partial h}{\partial \xi} + x_\xi \frac{\partial h}{\partial \eta} \right) \right] ds \quad (7.145)$$

And in case we have normal flow at the boundary ( $q = 0$  and  $x_\eta \partial q / \partial \eta = 0$ ) the boundary term reduces to:

$$\int_{\Gamma_{\xi\eta}} \left[ \frac{2r}{h} \left( -x_\eta \frac{\partial r}{\partial \xi} + x_\xi \frac{\partial r}{\partial \eta} \right) - \frac{r^2}{h^2} \left( -x_\eta \frac{\partial h}{\partial \xi} + x_\xi \frac{\partial h}{\partial \eta} \right) \right] ds \quad (7.146)$$

which will be approximated at the quadrature point  $qp$  and at time level  $n + \theta, p$

by

$$\underbrace{\frac{1}{2} \left[ \frac{2r}{h} \left( -x_\eta \frac{\partial r}{\partial \xi} + x_\xi \frac{\partial r}{\partial \eta} \right) - \frac{r^2}{h^2} \left( -x_\eta \frac{\partial h}{\partial \xi} + x_\xi \frac{\partial h}{\partial \eta} \right) \right]}_{\text{to right hand side}} + \quad (7.147)$$

$$+ \frac{1}{2} \theta \Delta h \underbrace{\left[ -\frac{2r}{h^2} \left( -x_\eta \frac{\partial r}{\partial \xi} + x_\xi \frac{\partial r}{\partial \eta} \right) + \frac{2r^2}{h^3} \left( -x_\eta \frac{\partial h}{\partial \xi} + x_\xi \frac{\partial h}{\partial \eta} \right) \right]}_{\mathcal{A}} + \quad (7.148)$$

$$+ \frac{1}{2} \theta \Delta r \underbrace{\left[ \frac{2}{h} \left( -x_\eta \frac{\partial r}{\partial \xi} + x_\xi \frac{\partial r}{\partial \eta} \right) - \frac{2r}{h^2} \left( -x_\eta \frac{\partial h}{\partial \xi} + x_\xi \frac{\partial h}{\partial \eta} \right) \right]}_{\mathcal{B}} + \quad (7.149)$$

$$+ \frac{1}{2} \theta \underbrace{\left( -\frac{r^2}{h^2} \right)}_{\mathcal{C}} \left( -x_\eta \frac{\partial \Delta h}{\partial \xi} + x_\xi \frac{\partial \Delta h}{\partial \eta} \right) + \frac{1}{2} \theta \underbrace{\frac{2r}{h}}_{\mathcal{D}} \left( -x_\eta \frac{\partial \Delta r}{\partial \xi} + x_\xi \frac{\partial \Delta r}{\partial \eta} \right) \quad (7.150)$$

where  $\mathcal{A}$ ,  $\mathcal{B}$ ,  $\mathcal{C}$  and  $\mathcal{D}$  multiplied by  $\frac{1}{2}\theta$  and *the geometrical factors* are the coefficients in the matrix of the  $\Delta$ -formulation.

### *Bed shear stress, momentum equation*

The bed shear stress term at the boundary reads:

$$\int_{\Gamma} c_f \left( \frac{\mathbf{q} |\mathbf{q}|}{h^2} \right) ds. \quad (7.151)$$

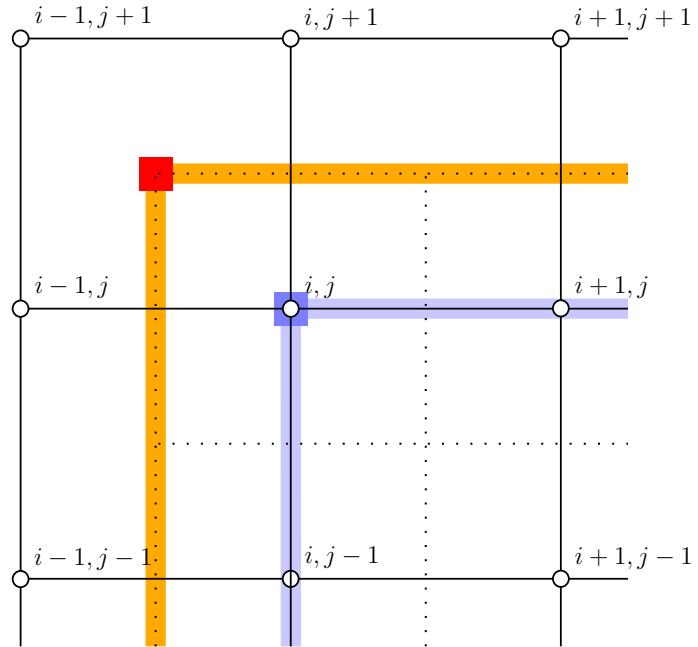
The components for the two momentum equations read:

$$F_q = \int_{\Gamma} c_f \left( \frac{q |\mathbf{q}|}{h^2} \right) ds, \quad q\text{-momentum eq.} \quad (7.152)$$

$$F_r = \int_{\Gamma} c_f \left( \frac{r |\mathbf{q}|}{h^2} \right) ds, \quad r\text{-momentum eq.} \quad (7.153)$$

**Not yet documented**

#### 7.1.4 Discretization at corner



**Figure 7.6:** Layout of the essential boundary (blue-line) and natural boundary (orange-line) in 2-dimensions on a structured grid at the upper-left corner. No line integrals are performed in the corner, so just the red-dot.

For the moment the following discretization is used for the upper left corner (north-west corner),  $u \in \{h, q, r\}$ , see Figure 7.6:

$$u_{i-1,j}^{n+\theta,p+1} - 2u_{i-1,j+1}^{n+\theta,p+1} + u_{i,j+1}^{n+\theta,p+1} = 0$$

The linearization around an iteration step  $p$  yields:

$$(u_{i-1,j}^{n+\theta,p} + \theta \Delta u_{i-1,j}) - 2(u_{i-1,j+1}^{n+\theta,p} + \theta \Delta u_{i-1,j+1}) + (u_{i,j+1}^{n+\theta,p} + \theta \Delta u_{i,j+1}) = 0 \quad (7.154)$$

$$\Leftrightarrow \quad (7.155)$$

$$\theta \Delta u_{i-1,j} - 2\theta \Delta u_{i-1,j+1} + \theta \Delta u_{i,j+1} + \left[ u_{i-1,j}^{n+\theta,p} - 2u_{i-1,j+1}^{n+\theta,p} + u_{i,j+1}^{n+\theta,p} \right] = 0 \quad (7.156)$$

Similar discretization are used for the other corners.

# 8 2D Wave numerical experiments

## 8.1 Gaussian hump

In this section some numerical results are given for the 2D Gaussian hump. The numerical tests are performed with some different time steps ( $\Delta t$ ), different space resolution (but with  $\Delta x = \Delta y$ ) and different geometry, but all with the same constant bed level at  $z_b = -10$  [m].

### 8.1.1 Gaussian hump

The considered 2-D wave equation reads:

$$\frac{\partial h}{\partial t} + \nabla \cdot \mathbf{q} = 0 \quad \text{continuity eq.} \quad (8.1)$$

$$\frac{\partial \mathbf{q}}{\partial t} + gh\nabla\zeta = 0 \quad \text{momentum eq.} \quad (8.2)$$

With initial conditions

$$h(x, y, 0) = \zeta(x, y, 0) - z_b(x, y), \quad [\text{m}] \quad (8.3)$$

$$q(x, y, 0) = 0, \quad [\text{m}^2 \text{s}^{-1}] \quad (8.4)$$

for the the water level a Gaussian hump is prescribed

$$\zeta(x, y) = a_0 \exp \left[ - \left( \frac{(x - \mu_x)^2}{2\sigma_x^2} + \frac{(y - \mu_y)^2}{2\sigma_y^2} \right) \right], \quad [\text{m}]. \quad (8.5)$$

At the boundaries no ingoing signals are prescribed, so outgoing signals are leaving the domain unhampered, which means no reflections will be present other then numerical reflections.

#### Numerical experiment

The numerical experiment is performed with the following parameters:

- Length of the domain,  $L_x = L_y = 6000$  [m], ranging from  $-3000$  [m] to  $3000$  [m].
- Bed level,  $z_b = -10$  [m].
- Grid size,  $\Delta x = \Delta y = 10$  [m].
- Start time,  $t_{start} = 0$  [s].
- End time,  $t_{stop} = 1800$  [s].
- Timestep,  $\Delta t = 10$  [s].
- Amplitude of the Gaussian hump,  $a_0 = 0.01$  [m].

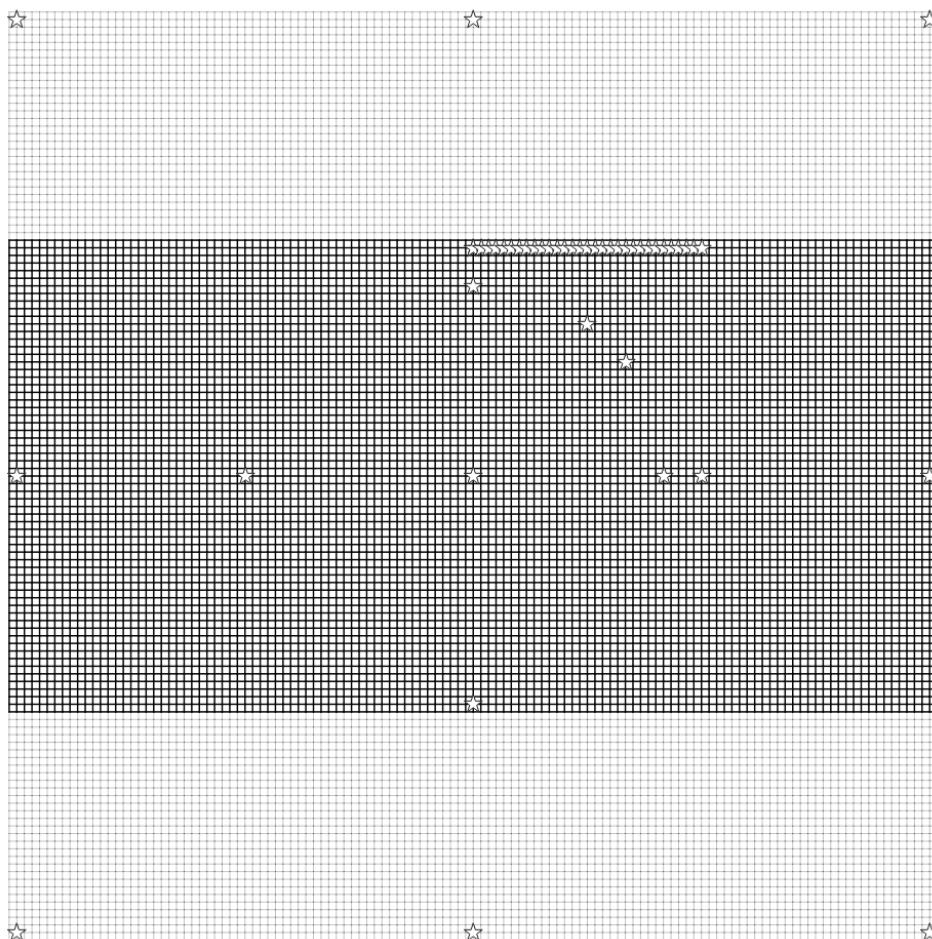
- Centre of the Gaussian hump,  $\mu_x = \mu_y = 0$  [m].
- Spreading of the Gaussian hump,  $\sigma_x = \sigma_y = 350$  [m].

### *Results of the numerical experiments 1*

**Not yet documented**

#### 8.1.2 Gaussian hump, reflection

The Gaussian hump test case is used to determine the reflection of a wave at the boundary. The schematization for this test is shown in [Figure 8.1](#).



**Figure 8.1:** Schematization area:  $[-6000, 6000] \times [-6000, 6000]$  [m] and  $[-6000, 6000] \times [-3000, 3000]$  [m]. The observation points at  $y = 3000$  [m] are present on both meshes and are used to determine the reflection of a wave at these locations.

The reflection coefficient is determined by:

$$R = \frac{|\max(h_{small}(t, \mathbf{x}_{obs})) - \max(h_{large}(t, \mathbf{x}_{obs}))|}{h_0} \times 100 \%, \quad 0 < t < 1800 \text{ [s]} \quad (8.6)$$

with

- |                    |  |
|--------------------|--|
| $R$                | Reflection coefficient, [-].   |
| $t$                | Simulation time, [s].  |
| $h_0$              | Still water depth, in both models the same, here 10 [m].                   |
| $h_{small}$        | Total water depth, in the small domain.                                    |
| $h_{large}$        | Total water depth, in the large domain.                                    |
| $\mathbf{x}_{obs}$ | Location of the coincide observation points in the small and large domain. |

### **Not yet documented**

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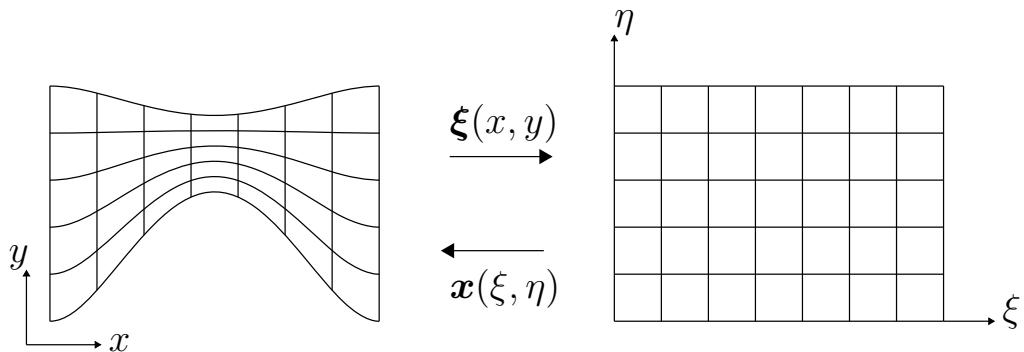
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# **Appendices**

# A Curvilinear coordinate transformation

A curvilinear coordinate transformation is employed to enable the calculation of non-rectangular bodies of water. Two grids are introduced: a curvilinear  $xy$ -grid, following the curvature of the shallow water body and a computational/numerical  $\xi\eta$ -grid, created by mapping the curvilinear  $xy$ -grid to an orthogonal coordinate system via a coordinate transformation. The global Cartesian  $xy$ -coordinate system is used for reference of the numerical grid. An example of this is sketched in [Figure A.1](#).



**Figure A.1:** Mesh mapping from the physical Cartesian  $xy$ -grid to the numerical  $\xi\eta$ -grid and vice versa.

Following the chain rule and assuming time-independent grids, we can express the differential operators in the global coordinate system as functions of the differential operators in the body-fitted curvilinear grid as follows:

$$\frac{\partial}{\partial x} = \frac{\partial \xi}{\partial x} \frac{\partial}{\partial \xi} + \frac{\partial \eta}{\partial x} \frac{\partial}{\partial \eta}, \quad (\text{A.1})$$

$$\frac{\partial}{\partial y} = \frac{\partial \xi}{\partial y} \frac{\partial}{\partial \xi} + \frac{\partial \eta}{\partial y} \frac{\partial}{\partial \eta}, \quad (\text{A.2})$$

in matrix-vector notation these equations reads:

$$\begin{pmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \end{pmatrix} = \begin{pmatrix} \frac{\partial \xi}{\partial x} & \frac{\partial \eta}{\partial x} \\ \frac{\partial \xi}{\partial y} & \frac{\partial \eta}{\partial y} \end{pmatrix} \begin{pmatrix} \frac{\partial}{\partial \xi} \\ \frac{\partial}{\partial \eta} \end{pmatrix}. \quad (\text{A.3})$$

where the transformation coefficients  $\frac{\partial \xi}{\partial x}$ ,  $\frac{\partial \eta}{\partial x}$ ,  $\frac{\partial \xi}{\partial y}$ ,  $\frac{\partial \eta}{\partial y}$  are unknown and but can be determined by the grid definitions.

The goal is to express the transformation coefficients of [equation \(A.3\)](#) in terms

of its inverted derivatives (grid definitions). The inverse transformation reads:

$$\begin{pmatrix} \frac{\partial}{\partial \xi} \\ \frac{\partial}{\partial \eta} \end{pmatrix} = \begin{pmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial y}{\partial \xi} \\ \frac{\partial x}{\partial \eta} & \frac{\partial y}{\partial \eta} \end{pmatrix} \begin{pmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \end{pmatrix}. \quad (\text{A.4})$$

We introduce a shorthand notation for the transformation coefficients with a subscript, e.g.  $\xi_x = \frac{\partial \xi}{\partial x}$  and calculate the inverse of the right-hand side to give:

$$\begin{pmatrix} x_\xi & y_\xi \\ x_\eta & y_\eta \end{pmatrix}^{-1} = \frac{1}{x_\xi y_\eta - y_\xi x_\eta} \begin{pmatrix} y_\eta & -y_\xi \\ -x_\eta & x_\xi \end{pmatrix} = \frac{1}{J} \begin{pmatrix} y_\eta & -y_\xi \\ -x_\eta & x_\xi \end{pmatrix} \quad (\text{A.5})$$

with the Jacobian determinant defined as:

$$J = \begin{vmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial x}{\partial \eta} \\ \frac{\partial y}{\partial \xi} & \frac{\partial y}{\partial \eta} \end{vmatrix} = x_\xi y_\eta - y_\xi x_\eta. \quad (\text{A.6})$$

leading to

$$\xi_x = \frac{1}{J} y_\eta, \quad \eta_x = -\frac{1}{J} y_\xi, \quad \xi_y = -\frac{1}{J} x_\eta, \quad \eta_y = \frac{1}{J} x_\xi. \quad (\text{A.7})$$

where  $J = x_\xi y_\eta - x_\eta y_\xi$  is the determinant of the coordinate transformation matrix.

Hence, we can use equation (A.7) to transform the partial derivatives (equation (A.3)) leading to:

$$\frac{\partial}{\partial x} = \xi_x \frac{\partial}{\partial \xi} + \eta_x \frac{\partial}{\partial \eta} = \frac{1}{J} \left( y_\eta \frac{\partial}{\partial \xi} - y_\xi \frac{\partial}{\partial \eta} \right) \quad (\text{A.8})$$

$$\frac{\partial}{\partial y} = \xi_y \frac{\partial}{\partial \xi} + \eta_y \frac{\partial}{\partial \eta} = \frac{1}{J} \left( -x_\eta \frac{\partial}{\partial \xi} + x_\xi \frac{\partial}{\partial \eta} \right) \quad (\text{A.9})$$

### *Second derivatives*

Second derivatives are instead transformed by applying this operator twice. This yields:

$$\frac{\partial^2}{\partial x^2} = \frac{1}{J} \left[ y_\eta \frac{\partial}{\partial \xi} \left( \frac{1}{J} \left( y_\eta \frac{\partial}{\partial \xi} - y_\xi \frac{\partial}{\partial \eta} \right) \right) - y_\xi \frac{\partial}{\partial \eta} \left( \frac{1}{J} \left( y_\eta \frac{\partial}{\partial \xi} - y_\xi \frac{\partial}{\partial \eta} \right) \right) \right], \quad (\text{A.10})$$

$$\frac{\partial^2}{\partial y^2} = \frac{1}{J} \left[ -x_\eta \frac{\partial}{\partial \xi} \left( \frac{1}{J} \left( -x_\eta \frac{\partial}{\partial \xi} + x_\xi \frac{\partial}{\partial \eta} \right) \right) + x_\xi \frac{\partial}{\partial \eta} \left( \frac{1}{J} \left( -x_\eta \frac{\partial}{\partial \xi} + x_\xi \frac{\partial}{\partial \eta} \right) \right) \right], \quad (\text{A.11})$$

which can be rewritten to:

$$\begin{aligned} \frac{\partial^2}{\partial x^2} &= \frac{y_\eta}{J^2} y_\eta \frac{\partial^2}{\partial \xi^2} + y_\xi \frac{y_\xi}{J^2} \frac{\partial^2}{\partial \eta^2} - 2 \frac{y_\eta}{J^2} y_\xi \frac{\partial^2}{\partial \xi \partial \eta} + \\ &+ \left( \frac{y_\xi y_\eta J_\eta}{J^3} - \frac{y_\eta^2 J_\xi}{J^3} + \frac{y_\eta y_\xi \eta}{J^2} - \frac{y_\eta y_\xi \eta}{J^2} \right) \frac{\partial}{\partial \xi} + \\ &+ \left( \frac{y_\eta y_\xi J_\xi}{J^3} - \frac{y_\xi^2 J_\eta}{J^3} + \frac{y_\xi y_\eta \xi}{J^2} - \frac{y_\xi y_\eta \xi}{J^2} \right) \frac{\partial}{\partial \eta} \end{aligned} \quad (\text{A.12})$$

$$\begin{aligned}\frac{\partial^2}{\partial y^2} &= x_\eta \frac{x_\eta}{J^2} \frac{\partial^2}{\partial \xi^2} + x_\xi \frac{x_\xi}{J^2} \frac{\partial^2}{\partial \eta^2} - 2x_\xi \frac{x_\eta}{J^2} \frac{\partial^2}{\partial \xi \partial \eta} + \\ &+ \left( \frac{x_\xi x_\eta J_\eta}{J^3} - \frac{x_\eta^2 J_\xi}{J^3} + \frac{x_{\xi\eta} x_\eta}{J^2} - \frac{x_{\eta\eta} x_\xi}{J^2} \right) \frac{\partial}{\partial \xi} + \\ &+ \left( \frac{x_\eta x_\xi J_\xi}{J^3} - \frac{x_\xi^2 J_\eta}{J^3} + \frac{x_{\xi\eta} x_\xi}{J^2} - \frac{x_{\xi\xi} x_\eta}{J^2} \right) \frac{\partial}{\partial \eta},\end{aligned}\quad (\text{A.13})$$

after repeated application of the chain rule, which should equal the application of the chain rule directly:

$$\frac{\partial^2}{\partial x^2} = \xi_x^2 \frac{\partial^2}{\partial \xi^2} + \eta_x^2 \frac{\partial^2}{\partial \eta^2} + 2\eta_x \xi_x \frac{\partial^2}{\partial \xi \partial \eta} + \xi_{xx} \frac{\partial}{\partial \xi} + \eta_{xx} \frac{\partial}{\partial \eta}, \quad (\text{A.14})$$

$$\frac{\partial^2}{\partial y^2} = \xi_y^2 \frac{\partial^2}{\partial \xi^2} + \eta_y^2 \frac{\partial^2}{\partial \eta^2} + 2\eta_y \xi_y \frac{\partial^2}{\partial \xi \partial \eta} + \xi_{yy} \frac{\partial}{\partial \xi} + \eta_{yy} \frac{\partial}{\partial \eta}. \quad (\text{A.15})$$

from which we can find the following relations:

$$\xi_{xx} = \frac{y_\xi y_\eta J_\eta}{J^3} - \frac{y_\eta^2 J_\xi}{J^3} + \frac{y_\eta y_\xi \eta_\eta}{J^2} - \frac{y_{\eta\eta} y_\xi}{J^2} \quad (\text{A.16})$$

$$\eta_{xx} = \frac{y_\eta y_\xi J_\xi}{J^3} - \frac{y_\xi^2 J_\eta}{J^3} + \frac{y_{\xi\eta} y_\xi}{J^2} - \frac{y_{\xi\xi} y_\eta}{J^2} \quad (\text{A.17})$$

$$\xi_{yy} = \frac{x_\xi x_\eta J_\eta}{J^3} - \frac{x_\eta^2 J_\xi}{J^3} + \frac{x_{\xi\eta} x_\eta}{J^2} - \frac{x_{\eta\eta} x_\xi}{J^2} \quad (\text{A.18})$$

$$\eta_{yy} = \frac{x_\eta x_\xi J_\xi}{J^3} - \frac{x_\xi^2 J_\eta}{J^3} + \frac{x_{\xi\eta} x_\xi}{J^2} - \frac{x_{\xi\xi} x_\eta}{J^2} \quad (\text{A.19})$$

## A.1 Transforming the terms

For completeness, we show the transformation of various terms here since some particular choices will be made to ease the implementation. For example, transforming the spatial derivatives in the continuity equation in a conservative form

$$\frac{\partial q}{\partial x} + \frac{\partial r}{\partial y} = \frac{1}{J} \left( y_\eta \frac{\partial q}{\partial \xi} - y_\xi \frac{\partial q}{\partial \eta} + \left( -x_\eta \frac{\partial r}{\partial \xi} + x_\xi \frac{\partial r}{\partial \eta} \right) \right) \quad (\text{A.20})$$

and adding  $(y_{\eta\xi} - y_{\xi\eta})q = 0$  and  $(x_{\eta\xi} - x_{\xi\eta})r = 0$ , yields

$$\frac{\partial q}{\partial x} + \frac{\partial r}{\partial y} = \frac{1}{J} \left( y_\eta \frac{\partial q}{\partial \xi} - y_\xi \frac{\partial q}{\partial \eta} + \color{blue}{y_{\eta\xi} q - y_{\xi\eta} q} \right. \quad (\text{A.21})$$

$$\left. - x_\eta \frac{\partial r}{\partial \xi} + x_\xi \frac{\partial r}{\partial \eta} + \color{blue}{x_{\eta\xi} r - x_{\xi\eta} r} \right) \quad (\text{A.22})$$

$$= \frac{1}{J} \left( \frac{\partial}{\partial \xi} (y_\eta q - x_\eta r) + \frac{\partial}{\partial \eta} (-y_\xi q + x_\xi r) \right), \quad (\text{A.23})$$

Taking the finite volume approach, yields

$$\frac{1}{J} \int_{\Omega_{\xi\eta}} \begin{pmatrix} \frac{\partial}{\partial\xi} \\ \frac{\partial}{\partial\eta} \end{pmatrix} \cdot \begin{pmatrix} y_\eta q - x_\eta r \\ -y_\xi q + x_\xi r \end{pmatrix} dl = \frac{1}{J} \oint_{\partial\Omega_{\xi\eta}} \begin{pmatrix} y_\eta q - x_\eta r \\ -y_\xi q + x_\xi r \end{pmatrix} \cdot \begin{pmatrix} n_\xi \\ n_\eta \end{pmatrix} dl = \quad (\text{A.24})$$

$$\frac{1}{J} \oint_{\partial\Omega_{\xi\eta}} ((y_\eta q - x_\eta r) n_\xi + (-y_\xi q + x_\xi r) n_\eta) dl \quad (\text{A.25})$$

### A.1.1 Convection term

The convection term in the  $x$ -momentum equation can be transformed as:

$$\frac{\partial(q^2/h)}{\partial x} + \frac{\partial(qr/h)}{\partial y} = \quad (\text{A.26})$$

$$= \frac{1}{J} \left( y_\eta \frac{\partial(q^2/h)}{\partial\xi} - y_\xi \frac{\partial(q^2/h)}{\partial\eta} - x_\eta \frac{\partial(qr/h)}{\partial\xi} + x_\xi \frac{\partial(qr/h)}{\partial\eta} \right) = \quad (\text{A.27})$$

$$\begin{aligned} &= \frac{1}{J} \left( y_\eta \frac{\partial(q^2/h)}{\partial\xi} - y_\xi \frac{\partial(q^2/h)}{\partial\eta} + \frac{q^2}{h} y_{\xi\eta} - \frac{q^2}{h} y_{\eta\xi} + \right. \\ &\quad \left. - x_\eta \frac{\partial(qr/h)}{\partial\xi} + x_\xi \frac{\partial(qr/h)}{\partial\eta} - \frac{qr}{h} x_{\xi\eta} + \frac{qr}{h} x_{\eta\xi} \right) = \end{aligned} \quad (\text{A.28})$$

$$= \frac{1}{J} \frac{\partial}{\partial\xi} \left( y_\eta \frac{q^2}{h} - x_\eta \frac{qr}{h} \right) + \frac{1}{J} \frac{\partial}{\partial\eta} \left( -y_\xi \frac{q^2}{h} + x_\xi \frac{qr}{h} \right). \quad (\text{A.29})$$

Taking the finite volume approach and applying Green's theorem, yields

$$\frac{1}{J} \oint_{\partial\Omega_{\xi\eta}} \left( \left( y_\eta \frac{q^2}{h} - x_\eta \frac{qr}{h} \right) n_\xi + \left( -y_\xi \frac{q^2}{h} + x_\xi \frac{qr}{h} \right) n_\eta \right) dl. \quad (\text{A.30})$$

which is equal to (and look to the similarity with [equation \(A.25\)](#))

$$\frac{1}{J} \oint_{\partial\Omega_{\xi\eta}} \left[ (y_\eta q - x_\eta r) \frac{q}{h} n_\xi + (-y_\xi q + x_\xi r) \frac{q}{h} n_\eta \right] dl. \quad (\text{A.31})$$

A similar transformation is valid for the convection term in the  $y$ -momentum equation, which reads

$$\frac{\partial(rq/h)}{\partial x} + \frac{\partial(r^2/h)}{\partial y} = \quad (\text{A.32})$$

$$= \frac{1}{J} \left( y_\eta \frac{\partial(rq/h)}{\partial\xi} - y_\xi \frac{\partial(rq/h)}{\partial\eta} - x_\eta \frac{\partial(r^2/h)}{\partial\xi} + x_\xi \frac{\partial(r^2/h)}{\partial\eta} \right) = \quad (\text{A.33})$$

$$\begin{aligned} &= \frac{1}{J} \left( y_\eta \frac{\partial(rq/h)}{\partial\xi} - y_\xi \frac{\partial(rq/h)}{\partial\eta} + \frac{rq}{h} y_{\xi\eta} - \frac{rq}{h} y_{\eta\xi} + \right. \\ &\quad \left. - x_\eta \frac{\partial(r^2/h)}{\partial\xi} + x_\xi \frac{\partial(r^2/h)}{\partial\eta} - \frac{r^2}{h} x_{\xi\eta} + \frac{r^2}{h} x_{\eta\xi} \right) = \end{aligned} \quad (\text{A.34})$$

$$= \frac{1}{J} \frac{\partial}{\partial \xi} \left( y_\eta \frac{rq}{h} - x_\eta \frac{r^2}{h} \right) + \frac{1}{J} \frac{\partial}{\partial \eta} \left( -y_\xi \frac{rq}{h} + x_\xi \frac{r^2}{h} \right). \quad (\text{A.35})$$

Taking the finite volume approach and applying Green's theorem, yields

$$\frac{1}{J} \oint_{\partial \Omega_{\xi\eta}} \left( \left( y_\eta \frac{rq}{h} - x_\eta \frac{r^2}{h} \right) n_\xi + \left( -y_\xi \frac{rq}{h} + x_\xi \frac{r^2}{h} \right) n_\eta \right) dl \quad (\text{A.36})$$

which is equal to (and look to the similarity with equation (A.25))

$$\frac{1}{J} \oint_{\partial \Omega_{\xi\eta}} \left[ (y_\eta q - x_\eta r) \frac{r}{h} n_\xi + (-y_\xi q + x_\xi r) \frac{r}{h} n_\eta \right] dl \quad (\text{A.37})$$

## A.1.2 Viscosity term

The  $x$  and  $y$ -momentum equation diffusion terms are treated here as well due to their complexity. They can be transformed as:

$$\frac{\partial}{\partial x} \left( 2\nu h \frac{\partial(q/h)}{\partial x} \right) = \quad (\text{A.38})$$

$$= \frac{1}{J} \left[ y_\eta \frac{\partial}{\partial \xi} \left( \frac{2\nu h}{J} \left( y_\eta \frac{\partial(q/h)}{\partial \xi} - y_\xi \frac{\partial(q/h)}{\partial \eta} \right) \right) - y_\xi \frac{\partial}{\partial \eta} \left( \frac{2\nu h}{J} \left( y_\eta \frac{\partial(q/h)}{\partial \xi} - y_\xi \frac{\partial(q/h)}{\partial \eta} \right) \right) \right] = \quad (\text{A.39})$$

$$= \frac{1}{J} \left[ y_\eta \left( \frac{\partial}{\partial \xi} \left( \frac{2\nu h}{J} \right) \left( y_\eta \frac{\partial(q/h)}{\partial \xi} - y_\xi \frac{\partial(q/h)}{\partial \eta} \right) + \frac{2\nu h}{J} \frac{\partial}{\partial \xi} \left( y_\eta \frac{\partial(q/h)}{\partial \xi} - y_\xi \frac{\partial(q/h)}{\partial \eta} \right) \right) + - y_\xi \left( \frac{\partial}{\partial \eta} \left( \frac{2\nu h}{J} \right) \left( y_\eta \frac{\partial(q/h)}{\partial \xi} - y_\xi \frac{\partial(q/h)}{\partial \eta} \right) + \frac{2\nu h}{J} \frac{\partial}{\partial \eta} \left( y_\eta \frac{\partial(q/h)}{\partial \xi} - y_\xi \frac{\partial(q/h)}{\partial \eta} \right) \right) \right] = \quad (\text{A.40})$$

$$= \frac{2}{J} \left[ y_\eta \left( \frac{\partial}{\partial \xi} \left( \frac{\nu h}{J} \right) \left( y_\eta \frac{\partial(q/h)}{\partial \xi} - y_\xi \frac{\partial(q/h)}{\partial \eta} \right) + \frac{\nu h}{J} \frac{\partial}{\partial \xi} \left( y_\eta \frac{\partial(q/h)}{\partial \xi} - y_\xi \frac{\partial(q/h)}{\partial \eta} \right) \right) + - y_\xi \left( \frac{\partial}{\partial \eta} \left( \frac{\nu h}{J} \right) \left( y_\eta \frac{\partial(q/h)}{\partial \xi} - y_\xi \frac{\partial(q/h)}{\partial \eta} \right) + \frac{\nu h}{J} \frac{\partial}{\partial \eta} \left( y_\eta \frac{\partial(q/h)}{\partial \xi} - y_\xi \frac{\partial(q/h)}{\partial \eta} \right) \right) \right] \quad (\text{A.41})$$

for the  $x$ -momentum equation the viscous terms can be transformed as:

$$-\frac{\partial}{\partial x} \left( 2\nu h \frac{\partial(q/h)}{\partial x} \right) - \frac{\partial}{\partial y} \left( \nu h \frac{\partial(r/h)}{\partial x} + \nu h \frac{\partial(q/h)}{\partial y} \right) = \quad (\text{A.42})$$

*step 1*

$$= - \frac{y_\eta}{J} \frac{\partial}{\partial \xi} \left( 2\nu h \frac{\partial(q/h)}{\partial x} \right) + \frac{y_\xi}{J} \frac{\partial}{\partial \eta} \left( 2\nu h \frac{\partial(q/h)}{\partial x} \right) + \\ + \frac{x_\eta}{J} \frac{\partial}{\partial \xi} \left( \nu h \frac{\partial(r/h)}{\partial x} + \nu h \frac{\partial(q/h)}{\partial y} \right) - \frac{x_\xi}{J} \frac{\partial}{\partial \eta} \left( \nu h \frac{\partial(r/h)}{\partial x} + \nu h \frac{\partial(q/h)}{\partial y} \right) \quad (\text{A.43})$$

assume  $x_{\xi\eta} - x_{\eta\xi} = 0$  and  $y_{\xi\eta} - y_{\eta\xi} = 0$

$$= -\frac{1}{J} \frac{\partial}{\partial \xi} \left[ 2\nu y_\eta h \frac{\partial(q/h)}{\partial x} - \nu h x_\eta \frac{\partial(r/h)}{\partial x} + \nu h x_\eta \frac{\partial(q/h)}{\partial y} \right] + \\ + \frac{1}{J} \frac{\partial}{\partial \eta} \left[ 2\nu y_\xi h \frac{\partial(q/h)}{\partial x} - \nu h x_\xi \frac{\partial(r/h)}{\partial x} + \nu h x_\xi \frac{\partial(q/h)}{\partial y} \right] \quad (\text{A.44})$$

*step 2*

$$= -\frac{1}{J} \frac{\partial}{\partial \xi} \left[ \frac{\nu h}{J} \left( 2y_\eta y_\eta \frac{\partial(q/h)}{\partial \xi} - 2y_\eta y_\xi \frac{\partial(q/h)}{\partial \eta} - x_\eta y_\eta \frac{\partial(r/h)}{\partial \xi} + x_\eta y_\xi \frac{\partial(r/h)}{\partial \eta} + \right. \right. \\ \left. \left. - x_\eta x_\eta \frac{\partial(q/h)}{\partial \xi} + x_\eta x_\xi \frac{\partial(q/h)}{\partial \eta} \right) \right] + \\ + \frac{1}{J} \frac{\partial}{\partial \eta} \left[ \frac{\nu h}{J} \left( 2y_\xi y_\eta \frac{\partial(q/h)}{\partial \xi} - 2y_\xi y_\xi \frac{\partial(q/h)}{\partial \eta} - x_\xi y_\eta \frac{\partial(r/h)}{\partial \xi} + x_\xi y_\xi \frac{\partial(r/h)}{\partial \eta} + \right. \right. \\ \left. \left. - x_\xi x_\eta \frac{\partial(q/h)}{\partial \xi} + x_\xi x_\xi \frac{\partial(q/h)}{\partial \eta} \right) \right] \quad (\text{A.45})$$

assume  $x_{\xi\eta} - x_{\eta\xi} = 0$  and  $y_{\xi\eta} - y_{\eta\xi} = 0$

$$= -\frac{1}{J} \frac{\partial}{\partial \xi} \left[ \frac{\nu h}{J} \left( -x_\eta \frac{\partial}{\partial \xi} \left( x_\eta \frac{q}{h} + y_\eta \frac{r}{h} \right) + x_\eta \frac{\partial}{\partial \eta} \left( x_\xi \frac{q}{h} + y_\xi \frac{r}{h} \right) + \right. \right. \\ \left. \left. + 2y_\eta \frac{\partial(y_\eta q/h)}{\partial \xi} - 2y_\eta \frac{\partial(y_\xi q/h)}{\partial \eta} \right) \right] \\ + \frac{1}{J} \frac{\partial}{\partial \eta} \left[ \frac{\nu h}{J} \left( -x_\xi \frac{\partial}{\partial \xi} \left( x_\eta \frac{q}{h} + y_\eta \frac{r}{h} \right) + x_\xi \frac{\partial}{\partial \eta} \left( x_\xi \frac{q}{h} + y_\xi \frac{r}{h} \right) + \right. \right. \\ \left. \left. + 2y_\xi \frac{\partial(y_\eta q/h)}{\partial \xi} - 2y_\xi \frac{\partial(y_\xi q/h)}{\partial \eta} \right) \right] \quad (\text{A.46})$$

for the  $y$ -momentum equation the viscous terms can be transformed as:

$$-\frac{\partial}{\partial x} \left( \nu h \frac{\partial(r/h)}{\partial x} + \nu h \frac{\partial(q/h)}{\partial y} \right) - \frac{\partial}{\partial y} \left( 2\nu h \frac{\partial(r/h)}{\partial y} \right) = \quad (\text{A.47})$$

*step 1*

$$= -\frac{y_\eta}{J} \frac{\partial}{\partial \xi} \left( \nu h \frac{\partial(r/h)}{\partial x} + \nu h \frac{\partial(q/h)}{\partial y} \right) + \frac{y_\xi}{J} \frac{\partial}{\partial \eta} \left( \nu h \frac{\partial(r/h)}{\partial x} + \nu h \frac{\partial(q/h)}{\partial y} \right) + \\ + \frac{x_\eta}{J} \frac{\partial}{\partial \xi} \left( 2\nu h \frac{\partial(r/h)}{\partial y} \right) - \frac{x_\xi}{J} \frac{\partial}{\partial \eta} \left( 2\nu h \frac{\partial(r/h)}{\partial y} \right) = \quad (\text{A.48})$$

assume  $x_{\xi\eta} - x_{\eta\xi} = 0$  and  $y_{\xi\eta} - y_{\eta\xi} = 0$

$$= -\frac{1}{J} \frac{\partial}{\partial \xi} \left[ \nu h y_\eta \frac{\partial(r/h)}{\partial x} + \nu h y_\eta \frac{\partial(q/h)}{\partial y} - 2\nu h x_\eta \frac{\partial(r/h)}{\partial y} \right] + \\ + \frac{1}{J} \frac{\partial}{\partial \eta} \left[ \nu h y_\xi \frac{\partial(r/h)}{\partial x} + \nu h y_\xi \frac{\partial(q/h)}{\partial y} - 2\nu h x_\xi \frac{\partial(r/h)}{\partial y} \right] = \quad (\text{A.49})$$

*step 2*

$$= -\frac{1}{J} \frac{\partial}{\partial \xi} \left[ \frac{\nu h}{J} \left( y_\eta y_\eta \frac{\partial(r/h)}{\partial \xi} - y_\eta y_\xi \frac{\partial(r/h)}{\partial \eta} + y_\eta x_\eta \frac{\partial(q/h)}{\partial \xi} - y_\eta x_\xi \frac{\partial(q/h)}{\partial \eta} + \right. \right. \\ \left. \left. + 2x_\eta x_\eta \frac{\partial(r/h)}{\partial \xi} - 2x_\xi x_\eta \frac{\partial(r/h)}{\partial \eta} \right) \right] + \\ + \frac{1}{J} \frac{\partial}{\partial \eta} \left[ \frac{\nu h}{J} \left( y_\xi y_\eta \frac{\partial(r/h)}{\partial \xi} - y_\xi y_\xi \frac{\partial(r/h)}{\partial \eta} + y_\xi x_\eta \frac{\partial(q/h)}{\partial \xi} - y_\xi x_\xi \frac{\partial(q/h)}{\partial \eta} + \right. \right. \\ \left. \left. + 2x_\eta x_\xi \frac{\partial(r/h)}{\partial \xi} - 2x_\xi x_\xi \frac{\partial(r/h)}{\partial \eta} \right) \right] = \quad (\text{A.50})$$

$$= -\frac{1}{J} \frac{\partial}{\partial \xi} \left[ \frac{\nu h}{J} \left( y_\eta \frac{\partial}{\partial \xi} \left( y_\eta \frac{r}{h} + x_\eta \frac{q}{h} \right) - y_\eta \frac{\partial}{\partial \eta} \left( y_\xi \frac{r}{h} + x_\xi \frac{q}{h} \right) + \right. \right. \\ \left. \left. + 2x_\eta \frac{\partial(x_\eta r/h)}{\partial \xi} - 2x_\eta \frac{\partial(x_\xi r/h)}{\partial \eta} \right) \right] \\ + \frac{1}{J} \frac{\partial}{\partial \eta} \left[ \frac{\nu h}{J} \left( y_\xi \frac{\partial}{\partial \xi} \left( y_\eta \frac{r}{h} + x_\eta \frac{q}{h} \right) + \right. \right. \\ \left. \left. - y_\xi \frac{\partial}{\partial \eta} \left( y_\xi \frac{r}{h} + x_\xi \frac{q}{h} \right) + 2x_\xi \frac{\partial(x_\eta r/h)}{\partial \xi} - 2x_\xi \frac{\partial(x_\xi r/h)}{\partial \eta} \right) \right]. \quad (\text{A.51})$$

### A.1.2.1 For a cartesian grid

On a cartesian grid ( $y_\xi = x_\eta = 0$ ) and multiplied with  $J$  these viscous terms reduce for the  $x$ -momentum equation to:

$$- \frac{\partial}{\partial \xi} \left[ \frac{\nu h}{J} \left( 2y_\eta \frac{\partial}{\partial \xi} \left( y_\eta \frac{q}{h} \right) \right) \right] + \\ + \frac{\partial}{\partial \eta} \left[ \frac{\nu h}{J} \left( -x_\xi \frac{\partial}{\partial \xi} \left( y_\eta \frac{r}{h} \right) + x_\xi \frac{\partial}{\partial \eta} \left( x_\xi \frac{q}{h} \right) \right) \right] \quad (\text{A.52})$$

and for the  $y$ -momentum to:

$$\begin{aligned} & -\frac{\partial}{\partial\xi}\left[\frac{\nu h}{J}\left(y_\eta\frac{\partial}{\partial\xi}\left(y_\eta\frac{r}{h}\right)-y_\eta\frac{\partial}{\partial\eta}\left(x_\xi\frac{q}{h}\right)\right)\right]+ \\ & +\frac{\partial}{\partial\eta}\left[\frac{\nu h}{J}\left(-2x_\xi\frac{\partial}{\partial\eta}\left(x_\xi\frac{r}{h}\right)\right)\right]. \end{aligned} \quad (\text{A.53})$$

Applying Green's theorem yields

$$\begin{aligned} & -\left[\frac{\nu h}{J}\left(2y_\eta\frac{\partial}{\partial\xi}\left(y_\eta\frac{q}{h}\right)\right)\right]n_\xi+ \\ & +\left[\frac{\nu h}{J}\left(-x_\xi\frac{\partial}{\partial\xi}\left(y_\eta\frac{r}{h}\right)+x_\xi\frac{\partial}{\partial\eta}\left(x_\xi\frac{q}{h}\right)\right)\right]n_\eta \end{aligned} \quad (\text{A.54})$$

and for the  $y$ -momentum to:

$$\begin{aligned} & -\left[\frac{\nu h}{J}\left(y_\eta\frac{\partial}{\partial\xi}\left(y_\eta\frac{r}{h}\right)-y_\eta\frac{\partial}{\partial\eta}\left(x_\xi\frac{q}{h}\right)\right)\right]n_\xi+ \\ & +\left[\frac{\nu h}{J}\left(-2x_\xi\frac{\partial}{\partial\eta}\left(x_\xi\frac{r}{h}\right)\right)\right]n_\eta. \end{aligned} \quad (\text{A.55})$$

with  $\mathbf{n} = (n_\xi, n_\eta)^T$  the outward normal vector.

## A.2 Transformed 2D Shallow Water Equations

Given the above, the 2D Shallow water equations can be transformed to generalized coordinates, resulting in:

$$J\frac{\partial h}{\partial t}+\frac{\partial}{\partial\xi}(y_\eta q-x_\eta r)+\frac{\partial}{\partial\eta}(-y_\xi q+x_\xi r)=0, \quad (\text{A.56})$$

$$\begin{aligned} & J\frac{\partial q}{\partial t}+\frac{\partial}{\partial\xi}\left((y_\eta q-x_\eta r)\frac{q}{h}\right)+\frac{\partial}{\partial\eta}\left((-y_\xi q+x_\xi r)\frac{q}{h}\right)+gh\left(y_\eta\frac{\partial\zeta}{\partial\xi}-y_\xi\frac{\partial\zeta}{\partial\eta}\right)+ \\ & +Jc_f\frac{q|\mathbf{q}|}{h^2}+\frac{\partial}{\partial\xi}\left[\frac{\nu h}{J}\left(x_\eta\frac{\partial}{\partial\xi}\left(x_\eta\frac{q}{h}+y_\eta\frac{r}{h}\right)-x_\eta\frac{\partial}{\partial\eta}\left(x_\xi\frac{q}{h}+y_\xi\frac{r}{h}\right)\right.\right. \\ & \left.-2y_\eta\frac{\partial(y_\eta q/h)}{\partial\xi}+2y_\eta\frac{\partial(y_\xi q/h)}{\partial\eta}\right)+\frac{\partial}{\partial\eta}\left[\frac{\nu h}{J}\left(-x_\xi\frac{\partial}{\partial\xi}\left(x_\eta\frac{q}{h}+y_\eta\frac{r}{h}\right)\right.\right. \\ & \left.+x_\xi\frac{\partial}{\partial\eta}\left(x_\xi\frac{q}{h}+y_\xi\frac{r}{h}\right)+2y_\xi\frac{\partial(y_\eta q/h)}{\partial\xi}-2y_\xi\frac{\partial(y_\xi q/h)}{\partial\eta}\right)\left.\right]=0, \end{aligned} \quad (\text{A.57})$$

$$\begin{aligned}
& J \frac{\partial r}{\partial t} + \frac{\partial}{\partial \xi} \left( (y_\eta q - x_\eta r) \frac{r}{h} \right) + \frac{\partial}{\partial \eta} \left( (-y_\xi q + x_\xi r) \frac{r}{h} \right) + gh \left( -x_\eta \frac{\partial \zeta}{\partial \xi} + x_\xi \frac{\partial \zeta}{\partial \eta} \right) + \\
& + J c_f \frac{r |\mathbf{q}|}{h^2} + \frac{\partial}{\partial \xi} \left[ \frac{\nu h}{J} \left( -y_\eta \frac{\partial}{\partial \xi} \left( x_\eta \frac{q}{h} + y_\eta \frac{r}{h} \right) + \right. \right. \\
& \left. \left. + y_\eta \frac{\partial}{\partial \eta} \left( x_\xi \frac{q}{h} + y_\xi \frac{r}{h} \right) - 2x_\eta \frac{\partial(x_\eta r/h)}{\partial \xi} + 2x_\eta \frac{\partial(x_\xi r/h)}{\partial \eta} \right) \right] + \\
& + \frac{\partial}{\partial \eta} \left[ \frac{\nu h}{J} \left( y_\xi \frac{\partial}{\partial \xi} \left( x_\eta \frac{q}{h} + y_\eta \frac{r}{h} \right) + \right. \right. \\
& \left. \left. - y_\xi \frac{\partial}{\partial \eta} \left( x_\xi \frac{q}{h} + y_\xi \frac{r}{h} \right) + 2x_\xi \frac{\partial(x_\eta r/h)}{\partial \xi} - 2x_\xi \frac{\partial(x_\xi r/h)}{\partial \eta} \right) \right] = 0. \tag{A.58}
\end{aligned}$$

with transformation coefficients presented using the subscript notation. However, the above equations are in differential form. We will write the equations in an integral form:

$$\int \frac{\partial \mathbf{U}}{\partial t} dV + \int \nabla \cdot \mathbf{F} dV - \int \mathbf{S} dV = 0 \tag{A.59}$$

where the  $\nabla$ -operator for use in the  $\xi\eta$ -grid, now reads:

$$\nabla = \begin{pmatrix} \frac{\partial}{\partial \xi} \\ \frac{\partial}{\partial \eta} \end{pmatrix}, \tag{A.60}$$

However, this definition is not necessary yet as we will be applying Gauss' theorem (for internal points) to [equation \(A.59\)](#), which yields:

$$\int \frac{\partial \mathbf{U}}{\partial t} dV + \oint \mathbf{F} \cdot \mathbf{n} dS - \int \mathbf{S} dV = 0, \tag{A.61}$$

where  $\mathbf{F}$  consists of continuity, convective and viscous contributions which are split in  $\xi$  and  $\eta$  directions:

$$\mathbf{F}_{\text{cont},\xi} = \begin{pmatrix} y_\eta q - x_\eta r \\ 0 \\ 0 \end{pmatrix}, \quad \mathbf{F}_{\text{cont},\eta} = \begin{pmatrix} -y_\xi q + x_\xi r \\ 0 \\ 0 \end{pmatrix} \tag{A.62}$$

$$\mathbf{F}_{\text{conv},\xi} = \begin{pmatrix} 0 \\ y_\eta \frac{q^2}{h} - x_\eta \frac{qr}{h} \\ y_\eta \frac{qr}{h} - x_\eta \frac{r^2}{h} \end{pmatrix}, \quad \mathbf{F}_{\text{conv},\eta} = \begin{pmatrix} 0 \\ -y_\xi \frac{q^2}{h} + x_\xi \frac{qr}{h} \\ -y_\xi \frac{qr}{h} + x_\xi \frac{r^2}{h} \end{pmatrix} \tag{A.63}$$

$$\mathbf{F}_{\text{visc},\xi} = \begin{pmatrix} 0 \\ \frac{\nu h}{J} \left[ x_\eta \frac{\partial}{\partial \xi} \left( x_\eta \frac{q}{h} + y_\eta \frac{r}{h} \right) - x_\eta \frac{\partial}{\partial \eta} \left( x_\xi \frac{q}{h} + y_\xi \frac{r}{h} \right) - 2y_\eta \frac{\partial(y_\eta q/h)}{\partial \xi} + 2y_\eta \frac{\partial(y_\xi q/h)}{\partial \eta} \right] \\ \frac{\nu h}{J} \left[ -y_\eta \frac{\partial}{\partial \xi} \left( x_\eta \frac{q}{h} + y_\eta \frac{r}{h} \right) + y_\eta \frac{\partial}{\partial \eta} \left( x_\xi \frac{q}{h} + y_\xi \frac{r}{h} \right) - 2x_\eta \frac{\partial(x_\eta r/h)}{\partial \xi} + 2x_\eta \frac{\partial(x_\xi r/h)}{\partial \eta} \right] \end{pmatrix}. \tag{A.64}$$

$$\mathbf{F}_{\text{visc},\eta} = \begin{pmatrix} 0 \\ \frac{\nu h}{J} \left[ -x_\xi \frac{\partial}{\partial \xi} \left( x_\eta \frac{q}{h} + y_\eta \frac{r}{h} \right) + x_\xi \frac{\partial}{\partial \eta} \left( x_\xi \frac{q}{h} + y_\xi \frac{r}{h} \right) + 2y_\xi \frac{\partial(y_\eta q/h)}{\partial \xi} - 2y_\xi \frac{\partial(y_\xi q/h)}{\partial \eta} \right] \\ \frac{\nu h}{J} \left[ y_\xi \frac{\partial}{\partial \xi} \left( x_\eta \frac{q}{h} + y_\eta \frac{r}{h} \right) - y_\xi \frac{\partial}{\partial \eta} \left( x_\xi \frac{q}{h} + y_\xi \frac{r}{h} \right) + 2x_\xi \frac{\partial(x_\eta r/h)}{\partial \xi} - 2x_\xi \frac{\partial(x_\xi r/h)}{\partial \eta} \right] \end{pmatrix} \quad (\text{A.65})$$

Applying the chain rule to the derivatives of combined functions yields:

$$\mathbf{F}_{\text{visc},\xi} = \begin{pmatrix} 0 \\ \underbrace{-\frac{x_\eta q}{h^2} \frac{\partial(x_\eta h)}{\partial \xi} + \frac{x_\eta}{h} \frac{\partial(x_\eta q)}{\partial \xi} - \frac{x_\eta r}{h^2} \frac{\partial(y_\eta h)}{\partial \xi} + \frac{x_\eta}{h} \frac{\partial(y_\eta r)}{\partial \xi}}_{x_\eta \frac{\partial}{\partial \xi} (x_\eta \frac{q}{h} + y_\eta \frac{r}{h})} \\ \underbrace{-\frac{x_\eta}{h} \frac{\partial(x_\xi q)}{\partial \eta} + \frac{x_\eta q}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} - \frac{x_\eta}{h} \frac{\partial(y_\xi r)}{\partial \eta} + \frac{x_\eta r}{h^2} \frac{\partial(y_\xi h)}{\partial \eta}}_{-\frac{x_\eta \frac{\partial}{\partial \eta} (x_\xi \frac{q}{h} + y_\xi \frac{r}{h})}{h}} \\ \underbrace{-\frac{2y_\eta}{h} \frac{\partial(y_\eta q)}{\partial \xi} + \frac{2y_\eta q}{h^2} \frac{\partial(y_\eta h)}{\partial \xi} + \frac{2y_\eta}{h} \frac{\partial(y_\xi q)}{\partial \eta} - \frac{2y_\eta q}{h^2} \frac{\partial(y_\xi h)}{\partial \eta}}_{-\frac{2y_\eta \frac{\partial}{\partial \xi} (y_\eta \frac{q}{h} + y_\xi \frac{r}{h})}{h}} \\ \underbrace{-\frac{y_\eta}{h} \frac{\partial(x_\eta q)}{\partial \xi} + \frac{y_\eta q}{h^2} \frac{\partial(x_\eta h)}{\partial \xi} - \frac{y_\eta}{h} \frac{\partial(y_\eta r)}{\partial \xi} + \frac{y_\eta r}{h^2} \frac{\partial(y_\eta h)}{\partial \xi}}_{-\frac{y_\eta \frac{\partial}{\partial \xi} (x_\eta \frac{q}{h} + y_\eta \frac{r}{h})}{h}} \\ \underbrace{+\frac{y_\eta}{h} \frac{\partial(x_\xi q)}{\partial \eta} - \frac{y_\eta q}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} + \frac{y_\eta}{h} \frac{\partial(y_\xi r)}{\partial \eta} - \frac{y_\eta r}{h^2} \frac{\partial(y_\xi h)}{\partial \eta}}_{\frac{y_\eta \frac{\partial}{\partial \eta} (x_\xi \frac{q}{h} + y_\xi \frac{r}{h})}{h}} \\ \underbrace{-\frac{2x_\eta}{h} \frac{\partial(x_\eta r)}{\partial \xi} + \frac{2x_\eta r}{h^2} \frac{\partial(x_\eta h)}{\partial \xi} + \frac{2x_\eta}{h} \frac{\partial(x_\xi r)}{\partial \eta} - \frac{2x_\eta r}{h^2} \frac{\partial(x_\xi h)}{\partial \eta}}_{-\frac{2x_\eta \frac{\partial}{\partial \xi} (x_\eta \frac{r}{h})}{h} + \frac{2x_\eta \frac{\partial}{\partial \eta} (x_\xi \frac{r}{h})}{h}} \end{pmatrix} \quad (\text{A.66})$$

$$\mathbf{F}_{\text{visc},\eta} = \left( \begin{array}{c}
0 \\
\\
\underbrace{\frac{\nu h}{J} \left[ -\frac{x_\xi}{h} \frac{\partial(x_\eta q)}{\partial \xi} + \frac{x_\xi q}{h^2} \frac{\partial(x_\eta h)}{\partial \xi} - \frac{x_\xi}{h} \frac{\partial(y_\eta r)}{\partial \xi} + \frac{x_\xi r}{h^2} \frac{\partial(y_\eta h)}{\partial \xi} \right.} \\
\underbrace{\left. + \frac{x_\xi}{h} \frac{\partial(x_\xi q)}{\partial \eta} - \frac{x_\xi q}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} + \frac{y_\xi}{h} \frac{\partial(x_\xi r)}{\partial \eta} - \frac{y_\xi r}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} \right.} \\
\underbrace{\left. + \frac{2y_\xi}{h} \frac{\partial(y_\eta q)}{\partial \xi} - \frac{2y_\xi q}{h^2} \frac{\partial(y_\eta h)}{\partial \xi} - \frac{2y_\xi}{h} \frac{\partial(y_\xi q)}{\partial \eta} + \frac{2y_\xi q}{h^2} \frac{\partial(y_\xi h)}{\partial \eta} \right.} \\
\underbrace{\left. \frac{2y_\xi}{h} \frac{\partial(x_\eta q)}{\partial \xi} - \frac{y_\xi q}{h^2} \frac{\partial(x_\eta h)}{\partial \xi} + \frac{y_\xi}{h} \frac{\partial(y_\eta r)}{\partial \xi} + \frac{y_\xi r}{h^2} \frac{\partial(y_\eta h)}{\partial \xi} \right.} \\
\underbrace{\left. - \frac{y_\xi}{h} \frac{\partial(x_\xi q)}{\partial \eta} + \frac{y_\xi q}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} - \frac{y_\xi}{h} \frac{\partial(y_\xi r)}{\partial \eta} - \frac{y_\xi r}{h^2} \frac{\partial(y_\xi h)}{\partial \eta} \right.} \\
\underbrace{\left. + \frac{2x_\xi}{h} \frac{\partial(x_\eta r)}{\partial \xi} - \frac{2x_\xi r}{h^2} \frac{\partial(x_\eta h)}{\partial \xi} - \frac{2x_\xi}{h} \frac{\partial(x_\xi r)}{\partial \eta} + \frac{2x_\xi r}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} \right] \\
\underbrace{\left. 2x_\xi \frac{\partial(x_\eta r/h)}{\partial \xi} - 2x_\xi \frac{\partial(x_\xi r/h)}{\partial \eta} \right] \end{array} \right) \quad (\text{A.67})$$

The source terms are split again into pressure gradient and bed shear stress-based sources,  $\mathbf{S} = \mathbf{S}_{\text{pg}} + \mathbf{S}_{\text{bs}}$ . Note that the expression for the bed shear stress matches that presented before in ?? due to the absence of spatial derivatives.

$$\mathbf{S}_{\text{pg}} = \begin{pmatrix} 0 \\ gh \left( y_\eta \frac{\partial \zeta}{\partial \xi} - y_\xi \frac{\partial \zeta}{\partial \eta} \right) \\ gh \left( -x_\eta \frac{\partial \zeta}{\partial \xi} + x_\xi \frac{\partial \zeta}{\partial \eta} \right) \end{pmatrix}, \quad \mathbf{S}_{\text{bs}} = \begin{pmatrix} 0 \\ -J c_f \frac{q|\mathbf{q}|}{h^2} \\ -J c_f \frac{r|\mathbf{q}|}{h^2} \end{pmatrix}, \quad (\text{A.68})$$

### A.3 Jacobians of the flux and source terms

We will derive the Jacobians in the numerical grid from the above definitions of the flux and source terms.

### A.3.1 Continuity Flux Jacobians

In  $\xi$ , the continuity flux and its Jacobian read:

$$\mathbf{F}_{\text{cont},\xi} = \begin{pmatrix} y_\eta q - x_\eta r \\ 0 \\ 0 \end{pmatrix}, \quad \mathbf{J}_{\text{cont},\xi} = \begin{pmatrix} 0 & y_\eta & -x_\eta \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}. \quad (\text{A.69})$$

The continuity flux in  $\eta$  and its Jacobian read:

$$\mathbf{F}_{\text{cont},\eta} = \begin{pmatrix} -y_\xi q + x_\xi r \\ 0 \\ 0 \end{pmatrix}, \quad \mathbf{J}_{\text{cont},\eta} = \begin{pmatrix} 0 & -y_\xi & x_\xi \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}. \quad (\text{A.70})$$

### A.3.2 Convective Flux Jacobians

In  $\xi$ , the convective flux and its Jacobian read:

$$\mathbf{F}_{\text{conv},\xi} = \begin{pmatrix} 0 \\ y_\eta \frac{q^2}{h} - x_\eta \frac{qr}{h} \\ y_\eta \frac{qr}{h} - x_\eta \frac{r^2}{h} \end{pmatrix}, \quad (\text{A.71})$$

$$\mathbf{J}_{\text{conv},\xi} = \begin{pmatrix} 0 & 0 & 0 \\ -y_\eta \frac{q^2}{h^2} + x_\eta \frac{qr}{h^2} & y_\eta \frac{2q}{h} - x_\eta \frac{r}{h} & -x_\eta \frac{q}{h} \\ -y_\eta \frac{qr}{h^2} + x_\eta \frac{r^2}{h^2} & y_\eta \frac{q}{h} & y_\eta \frac{q}{h} - x_\eta \frac{2r}{h} \end{pmatrix}. \quad (\text{A.72})$$

The convective flux in  $\eta$  and its Jacobian read:

$$\mathbf{F}_{\text{conv},\eta} = \begin{pmatrix} 0 \\ -y_\xi \frac{q^2}{h} + x_\xi \frac{qr}{h} \\ -y_\xi \frac{qr}{h} + x_\xi \frac{r^2}{h} \end{pmatrix}, \quad (\text{A.73})$$

$$\mathbf{J}_{\text{conv},\eta} = \begin{pmatrix} 0 & 0 & 0 \\ +y_\xi \frac{q^2}{h^2} - x_\xi \frac{qr}{h^2} & -y_\xi \frac{2q}{h} + x_\xi \frac{r}{h} & -x_\xi \frac{q}{h} \\ +y_\xi \frac{qr}{h^2} - x_\xi \frac{r^2}{h^2} & y_\xi \frac{r}{h} & y_\xi \frac{q}{h} - x_\xi \frac{2r}{h} \end{pmatrix}. \quad (\text{A.74})$$

#### Transformed discharges

Or when taken into account the transformed discharges  $y_\eta q - x_\eta r$  and  $-y_\xi q + x_\xi r$

$$\mathbf{F}_{\text{conv},\xi} = \begin{pmatrix} 0 \\ \{y_\eta q - x_\eta r\} \frac{q}{h} \\ \{y_\eta q - x_\eta r\} \frac{r}{h} \end{pmatrix}, \quad (\text{A.75})$$

$$\mathbf{J}_{\text{conv},\xi} = \begin{pmatrix} 0 & 0 & 0 \\ -\{y_\eta q - x_\eta r\} \frac{q}{h^2} & \{y_\eta q - x_\eta r\} \frac{1}{h} + y_\eta \frac{q}{h} & -x_\eta \frac{q}{h} \\ -\{y_\eta q + x_\eta r\} \frac{r}{h^2} & y_\eta \frac{q}{h} & \{y_\eta q - x_\eta r\} \frac{1}{h} - x_\eta \frac{r}{h} \end{pmatrix}. \quad (\text{A.76})$$

The convective flux in  $\eta$  and its Jacobian read:

$$\mathbf{F}_{\text{conv},\eta} = \begin{pmatrix} 0 \\ \{-y_\xi q + x_\xi r\} \frac{q}{h} \\ \{-y_\xi q + x_\xi r\} \frac{r}{h} \end{pmatrix} \quad (\text{A.77})$$

$$\mathbf{J}_{\text{conv},\eta} = \begin{pmatrix} 0 & 0 & 0 \\ -\{-y_\xi q + x_\xi r\} \frac{q}{h^2} & \{-y_\xi q + x_\xi r\} \frac{1}{h} - y_\xi \frac{q}{h} & x_\xi \frac{q}{h} \\ -\{-y_\xi q + x_\xi r\} \frac{r}{h^2} & -y_\xi \frac{r}{h} & \{-y_\xi q + x_\xi r\} \frac{1}{h} + x_\xi \frac{r}{h} \end{pmatrix}. \quad (\text{A.78})$$

### A.3.3 Viscous Flux Jacobians

The viscous flux terms are not repeated here for brevity. The jacobians of  $\mathbf{F}_{\text{conv},\xi}$  and  $\mathbf{F}_{\text{conv},\eta}$  are extensive and split up in their respective columns, for example:

$$\mathbf{J}_{\mathbb{F},\xi} = \begin{pmatrix} \frac{\partial \mathbf{J}_{\mathbb{F},\xi}}{\partial h} & \frac{\partial \mathbf{J}_{\mathbb{F},\xi}}{\partial q} & \frac{\partial \mathbf{J}_{\mathbb{F},\xi}}{\partial r} \end{pmatrix} \quad (\text{A.79})$$

where the column vectors are:

$$\frac{\partial \mathbf{J}_{VF,\xi}}{\partial h} = \begin{pmatrix} 0 \\ \nu \left[ -\frac{x_\eta q}{h^2} \frac{\partial(x_\eta h)}{\partial \xi} + \frac{x_\eta}{h} \frac{\partial(x_\eta q)}{\partial \xi} - \frac{x_\eta r}{h^2} \frac{\partial(y_\eta h)}{\partial \xi} + \frac{x_\eta}{h} \frac{\partial(y_\eta r)}{\partial \xi} + \right. \\ \left. -\frac{x_\eta}{h} \frac{\partial(x_\xi q)}{\partial \eta} + \frac{x_\eta q}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} - \frac{x_\eta}{h} \frac{\partial(y_\xi r)}{\partial \eta} + \frac{x_\eta r}{h^2} \frac{\partial(y_\xi h)}{\partial \eta} + \right. \\ \left. -\frac{2y_\eta}{h} \frac{\partial(y_\eta q)}{\partial \xi} + \frac{2y_\eta q}{h^2} \frac{\partial(y_\eta h)}{\partial \xi} + \frac{2y_\eta}{h} \frac{\partial(y_\xi q)}{\partial \eta} - \frac{2y_\eta q}{h^2} \frac{\partial(y_\xi h)}{\partial \eta} \right] + \\ + \frac{\nu h}{J} \left[ \frac{x_\eta q}{2h^3} \frac{\partial(x_\eta h)}{\partial \xi} - \frac{x_\eta q}{h^2} \frac{\partial(x_\eta \cdot)}{\partial \xi} - \frac{x_\eta}{h^2} \frac{\partial(x_\eta q)}{\partial \xi} + \frac{x_\eta r}{2h^3} \frac{\partial(y_\eta h)}{\partial \xi} + \right. \\ \left. -\frac{x_\eta r}{h^2} \frac{\partial(y_\eta \cdot)}{\partial \xi} - \frac{x_\eta}{h^2} \frac{\partial(y_\eta r)}{\partial \xi} + \frac{x_\eta}{h^2} \frac{\partial(x_\xi q)}{\partial \eta} - \frac{x_\eta q}{2h^3} \frac{\partial(x_\xi h)}{\partial \eta} + \right. \\ \left. + \frac{x_\eta q}{h^2} \frac{\partial(x_\xi \cdot)}{\partial \eta} + \frac{x_\eta}{h^2} \frac{\partial(y_\xi r)}{\partial \eta} - \frac{x_\eta r}{2h^3} \frac{\partial(y_\xi h)}{\partial \eta} + \frac{2y_\eta}{h^2} \frac{\partial(y_\eta q)}{\partial \xi} + \right. \\ \left. -\frac{2y_\eta q}{2h^3} \frac{\partial(y_\eta h)}{\partial \xi} + \frac{2y_\eta q}{h^2} \frac{\partial(y_\eta \cdot)}{\partial \xi} - \frac{2y_\eta}{h^2} \frac{\partial(y_\xi q)}{\partial \eta} + \frac{2y_\eta q}{2h^3} \frac{\partial(y_\xi h)}{\partial \eta} - \frac{2y_\eta q}{h^2} \frac{\partial(y_\xi \cdot)}{\partial \eta} \right] \\ -\frac{2y_\eta}{h} \frac{\partial(x_\eta r)}{\partial \xi} + \frac{2x_\eta r}{h^2} \frac{\partial(x_\eta h)}{\partial \xi} + \frac{2x_\eta}{h} \frac{\partial(x_\xi r)}{\partial \eta} - \frac{2x_\eta r}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} + \\ + \frac{\nu h}{J} \left[ \frac{y_\eta}{h^2} \frac{\partial(x_\eta q)}{\partial \xi} - \frac{y_\eta q}{2h^3} \frac{\partial(x_\eta h)}{\partial \xi} + \frac{y_\eta q}{h^2} \frac{\partial(x_\eta \cdot)}{\partial \xi} + \frac{y_\eta r}{h^2} \frac{\partial(y_\eta h)}{\partial \xi} + \right. \\ \left. -\frac{y_\eta r}{2h^3} \frac{\partial(y_\eta h)}{\partial \xi} + \frac{y_\eta r}{h^2} \frac{\partial(y_\eta \cdot)}{\partial \xi} - \frac{y_\eta}{h^2} \frac{\partial(x_\xi q)}{\partial \eta} + \frac{y_\eta q}{2h^3} \frac{\partial(x_\xi h)}{\partial \eta} + \right. \\ \left. -\frac{y_\eta q}{h^2} \frac{\partial(x_\xi \cdot)}{\partial \eta} - \frac{y_\eta}{h^2} \frac{\partial(y_\xi r)}{\partial \eta} + \frac{y_\eta r}{2h^3} \frac{\partial(y_\xi h)}{\partial \eta} - \frac{y_\eta r}{h^2} \frac{\partial(y_\xi \cdot)}{\partial \eta} + \right. \\ \left. + \frac{2x_\eta}{h^2} \frac{\partial(x_\eta r)}{\partial \xi} - \frac{2x_\eta r}{2h^3} \frac{\partial(x_\eta h)}{\partial \xi} + \frac{2x_\eta r}{h^2} \frac{\partial(x_\eta \cdot)}{\partial \xi} - \frac{2x_\eta}{h^2} \frac{\partial(x_\xi r)}{\partial \eta} + \right. \\ \left. + \frac{2x_\eta r}{2h^3} \frac{\partial(x_\xi h)}{\partial \eta} - \frac{2x_\eta r}{h^2} \frac{\partial(x_\xi \cdot)}{\partial \eta} \right] \end{pmatrix} \quad (A.80)$$

$$\frac{\partial \mathbf{J}_{VF,\xi}}{\partial q} = \begin{pmatrix} 0 \\ \frac{\nu h}{J} \left[ -\frac{x_\eta}{h^2} \frac{\partial(x_\eta h)}{\partial \xi} + \frac{x_\eta}{h} \frac{\partial(x_\eta \cdot)}{\partial \xi} - \frac{x_\eta}{h} \frac{\partial(x_\xi \cdot)}{\partial \eta} + \frac{x_\eta}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} + \right. \\ \left. -\frac{2y_\eta}{h} \frac{\partial(y_\eta \cdot)}{\partial \xi} + \frac{2y_\eta}{h^2} \frac{\partial(y_\eta h)}{\partial \xi} + \frac{2y_\eta}{h} \frac{\partial(y_\xi \cdot)}{\partial \eta} - \frac{2y_\eta}{h^2} \frac{\partial(y_\xi h)}{\partial \eta} \right] \\ \frac{\nu h}{J} \left[ -\frac{y_\eta}{h} \frac{\partial(x_\eta \cdot)}{\partial \xi} + \frac{y_\eta}{h^2} \frac{\partial(x_\eta h)}{\partial \xi} + \frac{y_\eta}{h} \frac{\partial(x_\xi \cdot)}{\partial \eta} - \frac{y_\eta}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} \right] \end{pmatrix}, \quad (A.81)$$

and

$$\frac{\partial \mathbf{J}_{\text{VF},\xi}}{\partial r} = \begin{pmatrix} 0 \\ \frac{\nu h}{J} \left[ -\frac{x_\eta}{h^2} \frac{\partial(y_\eta h)}{\partial \xi} + \frac{x_\eta}{h} \frac{\partial(y_\eta \cdot)}{\partial \xi} + \right. \\ \left. -\frac{x_\eta}{h} \frac{\partial(y_\xi \cdot)}{\partial \eta} + \frac{x_\eta}{h^2} \frac{\partial(y_\xi h)}{\partial \eta} \right] \\ \frac{\nu h}{J} \left[ -\frac{y_\eta}{h} \frac{\partial(y_\eta \cdot)}{\partial \xi} + \frac{y_\eta}{h^2} \frac{\partial(y_\eta h)}{\partial \xi} + \right. \\ \left. + \frac{y_\eta}{h} \frac{\partial(y_\xi)}{\partial \eta} - \frac{y_\eta}{h^2} \frac{\partial(y_\xi h)}{\partial \eta} + \right. \\ \left. -\frac{2x_\eta}{h} \frac{\partial(x_\eta \cdot)}{\partial \xi} + \frac{2x_\eta}{h^2} \frac{\partial(x_\eta h)}{\partial \xi} + \frac{2x_\eta}{h} \frac{\partial(x_\xi \cdot)}{\partial \eta} - \frac{2x_\eta}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} \right] \end{pmatrix}, \quad (\text{A.82})$$

and in the  $\eta$ -direction:

$$\frac{\partial \mathbf{J}_{\text{VF},\eta}}{\partial h} = \begin{pmatrix} 0 \\ \frac{\nu}{J} \left[ -\frac{x_\xi}{h} \frac{\partial(x_\eta q)}{\partial \xi} + \frac{x_\xi q}{h^2} \frac{\partial(x_\eta h)}{\partial \xi} - \frac{x_\xi}{h} \frac{\partial(y_\eta r)}{\partial \xi} + \frac{x_\xi r}{h^2} \frac{\partial(y_\eta h)}{\partial \xi} + \right. \\ \left. + \frac{x_\xi}{h} \frac{\partial(x_\xi q)}{\partial \eta} - \frac{x_\xi q}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} + \frac{y_\xi}{h} \frac{\partial(x_\xi r)}{\partial \eta} - \frac{y_\xi r}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} + \right. \\ \left. + \frac{2y_\xi}{h} \frac{\partial(y_\eta q)}{\partial \xi} - \frac{2y_\xi q}{h^2} \frac{\partial(y_\eta h)}{\partial \xi} - \frac{2y_\xi}{h} \frac{\partial(y_\xi q)}{\partial \eta} + \frac{2y_\xi q}{h^2} \frac{\partial(y_\xi h)}{\partial \eta} \right] + \\ + \frac{\nu h}{J} \left[ + \frac{x_\xi}{h^2} \frac{\partial(x_\eta q)}{\partial \xi} - \frac{x_\xi q}{2h^3} \frac{\partial(x_\eta h)}{\partial \xi} + \frac{x_\xi q}{h^2} \frac{\partial(x_\eta \cdot)}{\partial \xi} + \frac{x_\xi}{h^2} \frac{\partial(y_\eta r)}{\partial \xi} + \right. \\ \left. - \frac{x_\xi r}{2h^3} \frac{\partial(y_\eta h)}{\partial \xi} + \frac{x_\xi r}{h^2} \frac{\partial(y_\eta \cdot)}{\partial \xi} - \frac{x_\xi}{h^2} \frac{\partial(x_\xi q)}{\partial \eta} + \frac{x_\xi q}{2h^3} \frac{\partial(x_\xi h)}{\partial \eta} + \right. \\ \left. - \frac{x_\xi q}{h^2} \frac{\partial(x_\xi \cdot)}{\partial \eta} - \frac{y_\xi}{h^2} \frac{\partial(x_\xi r)}{\partial \eta} + \frac{y_\xi r}{2h^3} \frac{\partial(x_\xi h)}{\partial \eta} - \frac{y_\xi r}{h^2} \frac{\partial(x_\xi \cdot)}{\partial \eta} + \right. \\ \left. - \frac{2y_\xi}{h^2} \frac{\partial(y_\eta q)}{\partial \xi} + \frac{2y_\xi q}{2h^3} \frac{\partial(y_\eta h)}{\partial \xi} - \frac{2y_\xi q}{h^2} \frac{\partial(y_\eta \cdot)}{\partial \xi} + \frac{2y_\xi}{h^2} \frac{\partial(y_\xi q)}{\partial \eta} + \right. \\ \left. - \frac{2y_\xi q}{2h^3} \frac{\partial(y_\xi h)}{\partial \eta} + \frac{2y_\xi q}{h^2} \frac{\partial(y_\xi \cdot)}{\partial \eta} \right] \\ \frac{\nu}{J} \left[ \frac{y_\xi}{h} \frac{\partial(x_\eta q)}{\partial \xi} - \frac{y_\xi q}{h^2} \frac{\partial(x_\eta h)}{\partial \xi} + \frac{y_\xi}{h} \frac{\partial(y_\eta r)}{\partial \xi} + \frac{y_\xi r}{h^2} \frac{\partial(y_\eta h)}{\partial \xi} + \right. \\ \left. - \frac{y_\xi}{h} \frac{\partial(x_\xi q)}{\partial \eta} + \frac{y_\xi q}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} - \frac{y_\xi}{h} \frac{\partial(y_\xi r)}{\partial \eta} - \frac{y_\xi r}{h^2} \frac{\partial(y_\xi h)}{\partial \eta} + \right. \\ \left. + \frac{2x_\xi}{h} \frac{\partial(x_\eta r)}{\partial \xi} - \frac{2x_\xi r}{h^2} \frac{\partial(x_\eta h)}{\partial \xi} - \frac{2x_\xi}{h} \frac{\partial(x_\xi r)}{\partial \eta} + \frac{2x_\xi r}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} \right] + \\ + \frac{\nu h}{J} \left[ -\frac{y_\xi}{h^2} \frac{\partial(x_\eta q)}{\partial \xi} + \frac{y_\xi q}{2h^3} \frac{\partial(x_\eta h)}{\partial \xi} - \frac{y_\xi q}{h^2} \frac{\partial(x_\eta \cdot)}{\partial \xi} - \frac{y_\xi}{h^2} \frac{\partial(y_\eta r)}{\partial \xi} + \right. \\ \left. - \frac{y_\xi r}{2h^3} \frac{\partial(y_\eta h)}{\partial \xi} + \frac{y_\xi r}{h^2} \frac{\partial(y_\eta \cdot)}{\partial \xi} + \frac{y_\xi}{h^2} \frac{\partial(x_\xi q)}{\partial \eta} - \frac{y_\xi q}{2h^3} \frac{\partial(x_\xi h)}{\partial \eta} + \right. \\ \left. + \frac{y_\xi q}{h^2} \frac{\partial(x_\xi \cdot)}{\partial \eta} + \frac{y_\xi}{h^2} \frac{\partial(y_\xi r)}{\partial \eta} + \frac{y_\xi r}{2h^3} \frac{\partial(y_\xi h)}{\partial \eta} - \frac{y_\xi r}{h^2} \frac{\partial(y_\xi \cdot)}{\partial \eta} + \right. \\ \left. - \frac{2x_\xi}{h^2} \frac{\partial(x_\eta r)}{\partial \xi} + \frac{2x_\xi r}{2h^3} \frac{\partial(x_\eta h)}{\partial \xi} - \frac{2x_\xi r}{h^2} \frac{\partial(x_\eta \cdot)}{\partial \xi} + \frac{2x_\xi}{h^2} \frac{\partial(x_\xi r)}{\partial \eta} + \right. \\ \left. - \frac{2x_\xi r}{2h^3} \frac{\partial(x_\xi h)}{\partial \eta} + \frac{2x_\xi r}{h^2} \frac{\partial(x_\xi \cdot)}{\partial \eta} \right] \end{pmatrix}, \quad (\text{A.83})$$

$$\frac{\partial \mathbf{J}_{VF,\eta}}{\partial q} = \begin{pmatrix} 0 \\ \frac{\nu h}{J} \left[ -\frac{x_\xi}{h} \frac{\partial(x_\eta \cdot)}{\partial \xi} + \frac{x_\xi}{h^2} \frac{\partial(x_\eta h)}{\partial \xi} + \frac{x_\xi}{h} \frac{\partial(x_\xi \cdot)}{\partial \eta} - \frac{x_\xi}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} + \right. \\ \left. + \frac{2y_\xi}{h} \frac{\partial(y_\eta \cdot)}{\partial \xi} - \frac{2y_\xi}{h^2} \frac{\partial(y_\eta h)}{\partial \xi} - \frac{2y_\xi}{h} \frac{\partial(y_\xi \cdot)}{\partial \eta} + \frac{2y_\xi}{h^2} \frac{\partial(y_\xi h)}{\partial \eta} \right] \\ \frac{\nu h}{J} \left[ \frac{y_\xi}{h} \frac{\partial(x_\eta \cdot)}{\partial \xi} - \frac{y_\xi}{h^2} \frac{\partial(x_\eta h)}{\partial \xi} - \frac{y_\xi}{h} \frac{\partial(x_\xi \cdot)}{\partial \eta} + \frac{y_\xi}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} \right] \end{pmatrix}, \quad (\text{A.84})$$

and

$$\frac{\partial \mathbf{J}_{VF,\eta}}{\partial r} = \begin{pmatrix} 0 \\ \frac{\nu h}{J} \left[ -\frac{x_\xi}{h} \frac{\partial(y_\eta \cdot)}{\partial \xi} + \frac{x_\xi}{h^2} \frac{\partial(y_\eta h)}{\partial \xi} + \frac{y_\xi}{h} \frac{\partial(x_\xi \cdot)}{\partial \eta} - \frac{y_\xi}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} \right] \\ \frac{\nu h}{J} \left[ + \frac{y_\xi}{h} \frac{\partial(y_\eta \cdot)}{\partial \xi} + \frac{y_\xi}{h^2} \frac{\partial(y_\eta h)}{\partial \xi} - \frac{y_\xi}{h} \frac{\partial(y_\xi \cdot)}{\partial \eta} - \frac{y_\xi}{h^2} \frac{\partial(y_\xi h)}{\partial \eta} + \right. \\ \left. + \frac{2x_\xi}{h} \frac{\partial(x_\eta \cdot)}{\partial \xi} - \frac{2x_\xi}{h^2} \frac{\partial(x_\eta h)}{\partial \xi} - \frac{2x_\xi}{h} \frac{\partial(x_\xi \cdot)}{\partial \eta} + \frac{2x_\xi}{h^2} \frac{\partial(x_\xi h)}{\partial \eta} \right] \end{pmatrix}, \quad (\text{A.85})$$

## B Error estimation

In this section a Fourier mode analysis for constant  $\Delta x$  and  $\Psi$  of equation (4.22) is given. For convenience the equation is repeated here:

$$\tilde{u} - \frac{\partial}{\partial x} \Psi \frac{\partial \tilde{u}}{\partial x} = u_{giv} \quad (\text{B.1})$$

The Fourier-mode transform of equation (4.22) reads, when  $\Delta x = \text{constant}$  and  $\Psi = c_\Psi \Delta x^2 = \text{constant}$ :

$$\tilde{u} \exp(\text{i}kx) (1 + \Psi k^2) = \mathcal{F}(u_{giv}) \quad (\text{B.2})$$

multiply  $\Psi$  by  $\Delta x^2 / \Delta x^2 = 1$  yields

$$\tilde{u} \exp(\text{i}kx) \left( 1 + \frac{\Psi}{\Delta x^2} (k \Delta x)^2 \right) = \mathcal{F}(u_{giv}) \quad (\text{B.3})$$

which is easier to use in the analysis due to the term  $k \Delta x$ .

The discretization of equation (4.28) with constant  $\Delta x$  and  $\Psi$  yields:

$$\left( \frac{1}{8} - c_\Psi \right) u_{i-1} + \left( \frac{6}{8} + 2c_\Psi \right) u_i + \left( \frac{1}{8} - c_\Psi \right) u_{i+1} = \quad (\text{B.4})$$

$$= \frac{1}{\Delta x} \int_{x_{i-1/2}}^{x_{i+1/2}} u_{giv} dx \quad (\text{B.5})$$

Substitution of the Fourier modes

$$\bar{u}_k = \bar{u}_k \exp(\text{i}k \Delta x) \quad \text{and} \quad u_{giv} = u_{giv,k} \exp(\text{i}k \Delta x) \quad (\text{B.6})$$

in this equation yields:

$$\bar{u}_k \left( \left( \frac{1}{8} - c_\Psi \right) \exp(-\text{i}k \Delta x) + \left( \frac{6}{8} + 2c_\Psi \right) + \left( \frac{1}{8} - c_\Psi \right) \exp(-\text{i}k \Delta x) \right) = \quad (\text{B.7})$$

$$= \frac{u_{giv,k}}{\Delta x} \int_{x_{i-1/2}}^{x_{i+1/2}} \exp(\text{i}k \Delta x) dx \quad (\text{B.8})$$

$\Rightarrow$

$$\begin{aligned} \bar{u}_k \left( \frac{6}{8} + 2c_\Psi + \left( \frac{1}{8} - c_\Psi \right) 2 \cos(k \Delta x) \right) &= \\ &= u_{giv,k} \frac{-\text{i}(\exp(\frac{\text{i}}{2}k \Delta x) - \exp(-\frac{\text{i}}{2}k \Delta x))}{k \Delta x} \quad (\text{B.9}) \end{aligned}$$

$\Leftrightarrow$

$$\bar{u}_k \left( \frac{6}{8} + 2c_\Psi + \left( \frac{1}{8} - c_\Psi \right) 2 \cos(k\Delta x) \right) = u_{giv,k} \frac{2 \sin(\frac{1}{2}k\Delta x)}{k\Delta x} \quad (\text{B.10})$$

The ratio between the regularized function  $\tilde{u}$  (equation (B.3)) and given function reads (see Figure B.1):

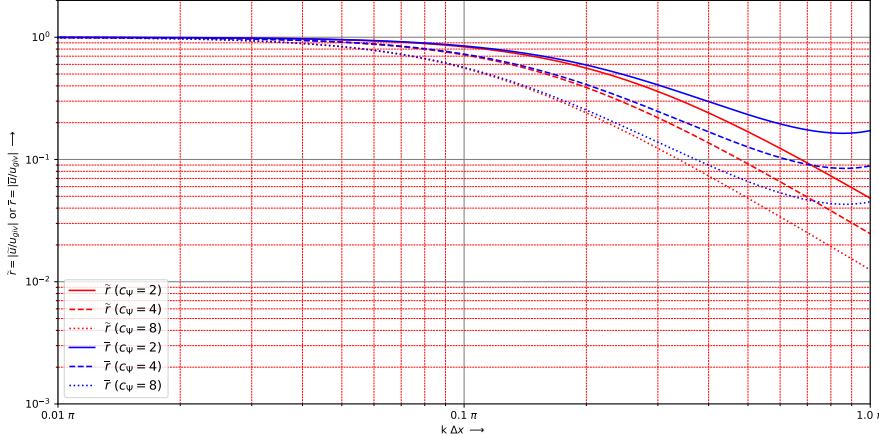
$$\tilde{r} = \left| \frac{\tilde{u}_k}{u_{giv,k}} \right| = \left| \frac{1}{1 + c_\Psi(k\Delta x)^2} \right| \quad (\text{B.11})$$

and the ratio between the piecewise linear function  $\bar{u}$  (equation (B.10)) and given function reads (see Figure B.1):

$$\bar{r} = \left| \frac{\bar{u}_k}{u_{giv,k}} \right| = \left| \frac{2 \sin(\frac{1}{2}k\Delta x)}{k\Delta x \left( \frac{6}{8} + 2c_\Psi + \left( \frac{1}{8} - c_\Psi \right) 2 \cos(k\Delta x) \right)} \right| \quad (\text{B.12})$$

$\Leftrightarrow$

$$\bar{r} = \left| \frac{\bar{u}_k}{u_{giv,k}} \right| = \left| \frac{8 \sin(\frac{1}{2}k\Delta x)}{k\Delta x \left( 3 + \cos(k\Delta x) + 8c_\Psi(1 - \cos(k\Delta x)) \right)} \right| \quad (\text{B.13})$$



**Figure B.1:** Ration between  $\tilde{r} = |\tilde{u}_k/u_{giv,k}|$ , and  $\bar{r} = |\bar{u}_k/u_{giv,k}|$ . For different values of  $c_\Psi = \Psi/\Delta x^2$ .

## B.1 Numerical error

Discretization error values are determined when  $\Delta x = constant$  and  $\Psi = 0$ , equation (4.28) reduces to:

$$\frac{1}{8}u_{i-1} + \frac{6}{8}u_i + \frac{1}{8}u_{i+1} = \frac{1}{\Delta x} \int_{x_{i-1/2}}^{x_{i+1/2}} u_{giv} dx \quad (\text{B.14})$$

Numerical error as discretized between grid points

$$\text{errorFVEgridpoint}(k\Delta x) = \left| 1 - \frac{8 \sin(\frac{1}{2}k\Delta x)}{k\Delta x(3 + \cos(k\Delta x))} \right| \quad (\text{B.15})$$

Numerical error as discretized between cell centres (numerical Fourier-mode through the cell centres)

$$\text{errorFVEcellcentre}(k\Delta x) = \left| 1 - \frac{8 \sin(\frac{1}{2}k\Delta x) \cos(\frac{1}{2}k\Delta x)}{k\Delta x(3 + \cos(k\Delta x))} \right| \quad (\text{B.16})$$

With lowest order estimation of (see [Borsboom \(2024\)](#)):

$$-\frac{1}{24}(k\Delta x)^2 - \frac{7}{960}(k\Delta x)^4 + O(\Delta x^6) \quad (\text{B.17})$$

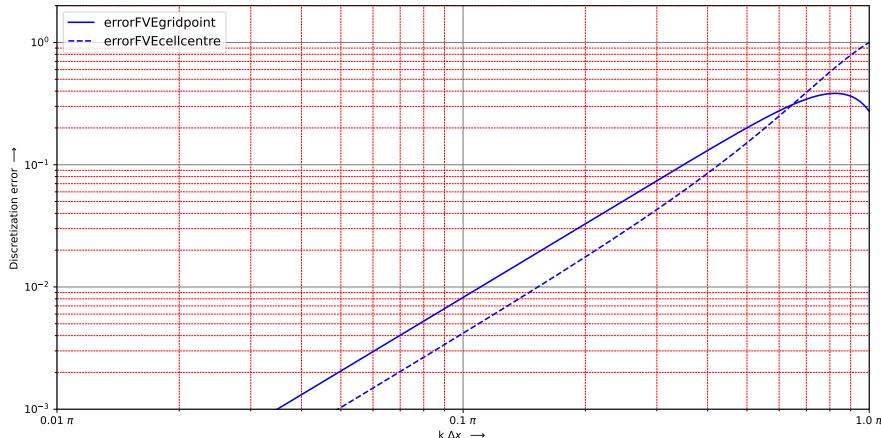
So if the numerical error needs to be smaller than 1 %, the number of grid cells per wave length ( $\lambda = N\Delta x$ ) is computed as

$$\frac{1}{24}(k\Delta x)^2 < 0.01 \Rightarrow k\Delta x < 0.5 \Rightarrow \quad (\text{B.18})$$

$$\left( \frac{2\pi}{N\Delta x} \right) \Delta x < 0.5 \Rightarrow N > 4\pi \approx 13 \quad (\text{B.19})$$

so per wave detail  $\approx 7$  grid cells.

Discretization error values are given when  $\Psi = c_\Psi \Delta x^2 = 0$  (see [Figure B.2](#)):



**Figure B.2:** Error function for value  $\Psi = c_\Psi \Delta x^2 = 0$ .

## B.2 Determining the factor $c_\Psi$

In the limit of  $k\Delta x \rightarrow \infty$  equation (B.11) behaves as:

$$\lim_{k\Delta x \rightarrow \infty} \frac{1}{1 + c_\Psi(k\Delta x)^2} = \frac{1}{c_\Psi(k\Delta x)^2} \quad (\text{B.20})$$

The cut-off frequency is determined by  $1 = 1/(c_\Psi(k\Delta x)^2)$ , hence filter parameter  $c_\Psi = 1/(k\Delta x)^2$  gives cut-off frequency  $k$ , or  $k\Delta x = \sqrt{1/c_\Psi}$  is obtained with filter parameter  $c_\Psi$ . Given the wave length from the required numerical error (1 %,  $N = 13$ ), the coefficient  $c_\Psi$  reads:

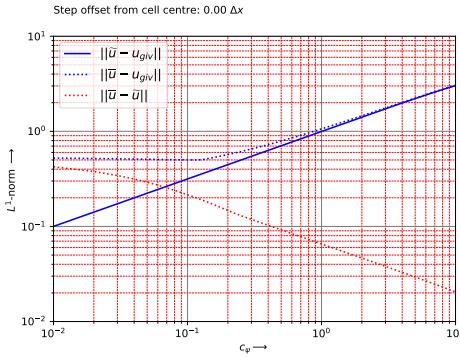
$$c_\Psi = \frac{1}{(k\Delta x)^2} \Rightarrow c_\Psi = \frac{N^2}{(2\pi)^2} \approx 4 \quad (\text{B.21})$$

**Table B.1:** Several typical values for numerical accuracy,  $c_\psi$  and number of nodes per wavelength ( $N$ ), the highlighted line is set as default.

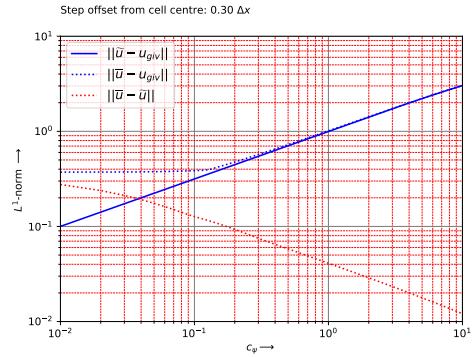
	Accuracy	$c_\Psi$	$N$
<b>1</b>	5 %	0.5	4.5
<b>2</b>	2 %	2	8.9
<b>3</b>	1 %	4	12.8
<b>4</b>	0.5 %	10	18.1

## B.3 $L^1$ -norm for the functions $\tilde{u}$ , $\bar{u}$ and $u_{given}$

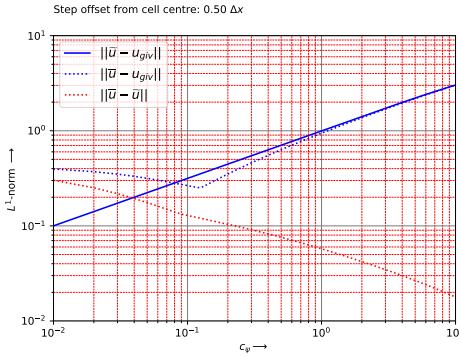
The next figures show the  $L^1$ -norm for the functions  $\|\tilde{u} - u_{giv}\|_1$ ,  $\|\bar{u} - u_{giv}\|_1$  and  $\|\bar{u} - \tilde{u}\|_1$



(a) Step defined at cell centre.



(b) Step defined with an off set of  $0.3 \Delta x$  from cell centre.

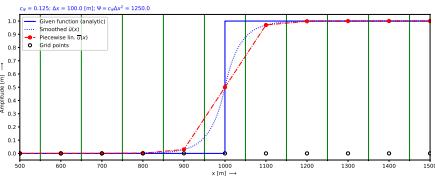


(c) Step defined with an off set of  $0.5 \Delta x$  from cell centre, thus defined at cell face.

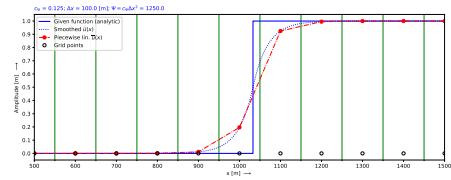
**Figure B.3:** Several plots of  $L^1$ -norm for different locations of the step.

As seen from these figures. When choosing  $c_\Psi > 4$  then the  $L^1$ -norm of  $\|\bar{u} - \tilde{u}\|_1$  is for all locations of the step smaller than  $2 \times 10^{-2}$  (red dotted lines in the plots). Also the blue and blue dotted line are close together for  $c_\Psi > 4$ . That is the region in which we want to have the discretisation because there is the difference between the piecewise linear numerical solution  $\bar{u}$  and the regularized solution  $\tilde{u}$  is independent of the location of the step, given by the function  $u_{giv}$ .

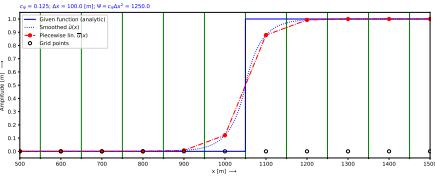
We also see that the dotted blue line is completely above the blue line if the step is located at the cell centre and with an offset of  $0.3\Delta x$  (see [Figure B.3a](#) and [Figure B.3b](#)) and it is partly below the blue line if the offset of the step is located at  $0.5\Delta x$  ([Figure B.3c](#)). The dotted blue line has also a sharp bend at the location where  $c_\Psi = 0.125$ . These approximations are presented in the [Figure B.4a](#), [Figure B.4b](#) and [Figure B.4c](#). As seen from these plot the piecewise linear approximation shown in [Figure B.4c](#) is closer to the Heaviside function as the other two approximations.



(a) Step defined at cell centre.



(b) Step defined with an offset of  $0.3 \Delta x$  from cell centre.



(c) Step defined with an offset of  $0.5 \Delta x$  from cell centre, thus defined at cell face.

**Figure B.4:** Several plots of the piecewise linear approximation ( $\bar{u}$ ) of the Heaviside function compared to the regularized function ( $\tilde{u}$ ).

## C Diagonalise 1-D wave equation with convection

The one dimensional shallow water equations with convection read

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = 0 \quad (\text{C.1})$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q^2}{h} \right) + gh \frac{\partial \zeta}{\partial x} = 0 \quad (\text{C.2})$$

Using  $\zeta = h + z_b$  in the momentum equation the system of equations is written as:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = 0 \quad (\text{C.3})$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q^2}{h} \right) + gh \frac{\partial h}{\partial x} = -gh \frac{\partial z_b}{\partial x} \quad (\text{C.4})$$

The convection term can be rewritten in the linear form for the derivatives as:

$$\frac{\partial}{\partial x} \left( \frac{q^2}{h} \right) = \frac{2q}{h} \frac{\partial q}{\partial x} - \frac{q^2}{h^2} \frac{\partial h}{\partial x} \quad (\text{C.5})$$

In matrix notation it reads ( $\zeta = h + z_b$  is used):

$$\begin{pmatrix} h \\ q \end{pmatrix}_t + \begin{pmatrix} 0 & 1 \\ gh - \frac{q^2}{h^2} & \frac{2q}{h} \end{pmatrix} \begin{pmatrix} h \\ q \end{pmatrix}_x = -gh \begin{pmatrix} 0 \\ z_b \end{pmatrix}_x \quad (\text{C.6})$$

To make the system of equations diagonal, we have to find the eigen values and the eigen vectors. The eigenvalues of the matrix are (using **Maplesoft**)

$$\lambda_1 = \frac{q}{h} + \sqrt{gh} \quad \text{and} \quad \lambda_2 = \frac{q}{h} - \sqrt{gh} \quad (\text{C.7})$$

The eigenvectors are

$$\begin{pmatrix} 1 \\ \frac{q}{h} + \sqrt{gh} \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} 1 \\ \frac{q}{h} - \sqrt{gh} \end{pmatrix} \quad (\text{C.8})$$

The diagonalised SWE with convection read (after multiplying by  $2\sqrt{gh}$ , using **Maplesoft**)

$$\begin{aligned} & \begin{pmatrix} \sqrt{gh} - \frac{q}{h} & 1 \\ \sqrt{gh} + \frac{q}{h} & -1 \end{pmatrix} \begin{pmatrix} h \\ q \end{pmatrix}_t + \begin{pmatrix} \frac{q}{h} + \sqrt{gh} & 0 \\ 0 & \frac{q}{h} - \sqrt{gh} \end{pmatrix} \begin{pmatrix} \sqrt{gh} - \frac{q}{h} & 1 \\ \sqrt{gh} + \frac{q}{h} & -1 \end{pmatrix} \begin{pmatrix} h \\ q \end{pmatrix}_x = \\ & = -gh \begin{pmatrix} \sqrt{gh} - \frac{q}{h} & 1 \\ \sqrt{gh} + \frac{q}{h} & -1 \end{pmatrix} \begin{pmatrix} 0 \\ z_b \end{pmatrix}_x \end{aligned} \quad (\text{C.9})$$

Written in two separate equations

$$\left( \sqrt{gh} - \frac{q}{h} \right) \frac{\partial h}{\partial t} + \frac{\partial q}{\partial t} + \left( \frac{q}{h} + \sqrt{gh} \right) \left( \left( \sqrt{gh} - \frac{q}{h} \right) \frac{\partial h}{\partial x} + \frac{\partial q}{\partial x} \right) = -gh \frac{\partial z_b}{\partial x} \quad \text{right going} \quad (\text{C.10})$$

$$\left( \sqrt{gh} + \frac{q}{h} \right) \frac{\partial h}{\partial t} - \frac{\partial q}{\partial t} + \left( \frac{q}{h} - \sqrt{gh} \right) \left( \left( \sqrt{gh} + \frac{q}{h} \right) \frac{\partial h}{\partial x} - \frac{\partial q}{\partial x} \right) = gh \frac{\partial z_b}{\partial x} \quad \text{left going} \quad (\text{C.11})$$

First rearrange the equation for the right going wave (keep in mind that also [equation \(C.5\)](#) is used):

$$\left( \sqrt{gh} - \frac{q}{h} \right) \frac{\partial h}{\partial t} + \frac{\partial q}{\partial t} + \left( gh - \frac{q^2}{h^2} \right) \frac{\partial h}{\partial x} + \left( \frac{q}{h} + \sqrt{gh} \right) \frac{\partial q}{\partial x} = -gh \frac{\partial z_b}{\partial x} \quad (\text{C.12})$$

$$\left( \sqrt{gh} - \frac{q}{h} \right) \left( \frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} \right) + \left( \frac{\partial q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q^2}{h} \right) + gh \frac{\partial \zeta}{\partial x} \right) = 0 \quad (\text{C.13})$$

and second, rearrange the equation for the left going wave:

$$\left( \sqrt{gh} + \frac{q}{h} \right) \frac{\partial h}{\partial t} - \frac{\partial q}{\partial t} + \left( \frac{q^2}{h^2} - gh \right) \frac{\partial h}{\partial x} - \left( \frac{q}{h} - \sqrt{gh} \right) \frac{\partial q}{\partial x} = gh \frac{\partial z_b}{\partial x} \quad (\text{C.14})$$

$$\left( \sqrt{gh} + \frac{q}{h} \right) \left( \frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} \right) - \left( \frac{\partial q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q^2}{h} \right) + gh \frac{\partial \zeta}{\partial x} \right) = 0 \quad (\text{C.15})$$

Which can be written as a combination of the continuity ([C.1](#)) and momentum equation ([C.2](#)) (see also [Borsboom \(2001, eq. 4\)](#)),

$$\begin{array}{ll} \text{right going} & \begin{pmatrix} \sqrt{gh} - \frac{q}{h} & 1 \\ \sqrt{gh} + \frac{q}{h} & -1 \end{pmatrix} \begin{array}{l} \text{continuity eq.} \\ \text{momentum eq.} \end{array} = 0 \\ \text{left going} & \end{array} \quad (\text{C.16})$$

or, after multiplying with  $h$

$$\begin{array}{ll} \text{right going} & \begin{pmatrix} h\sqrt{gh} - q & h \\ h\sqrt{gh} + q & -h \end{pmatrix} \begin{array}{l} \text{continuity eq.} \\ \text{momentum eq.} \end{array} = 0 \\ \text{left going} & \end{array} \quad (\text{C.17})$$

## D Error function needed to regularize the artificial viscosity

Regularization of the artificial viscosity, assumed to be independent of time, is described in [section 4.2](#). The mentioned error-function is derived in this section and is based on [Borsboom \(2001\)](#), eq. 42):

We start from the continuity and momentum equation for non-linear waves (i.e. [equation \(5.54\)](#) and [\(5.55\)](#)) and combine these two equations to one equation representing the energy.

The continuity and momentum equation read:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = 0 \quad \text{continuity eq.} \quad (\text{D.1})$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q^2}{h} \right) + gh \frac{\partial h}{\partial x} = 0 \quad \text{momentum eq.} \quad (\text{D.2})$$

a suitable combination of these two equations yields the energy equation. The suitable combination is:

$$\left( \frac{1}{2} \frac{q^2}{h^2} + g\zeta \right) (\text{continuity eq.}) + \frac{q}{h} (\text{momentum eq.}) = 0 \quad (\text{D.3})$$

and the energy equation reads:

$$\frac{\partial}{\partial t} \left( h \left( \frac{1}{2} \frac{q^2}{h^2} + g\zeta - \frac{1}{2} gh \right) \right) + \frac{\partial}{\partial x} \left( q \left( \frac{1}{2} \frac{q^2}{h^2} + g\zeta \right) \right) = 0 \quad (\text{D.4})$$

For a steady state solution ( $\partial/\partial t = 0$  and  $q = \text{Constant}$ ), when have:

$$\frac{\partial}{\partial x} \left( \frac{1}{2} \frac{q^2}{h^2} + g\zeta \right) = \frac{q}{h^2} \frac{\partial q}{\partial x} - \frac{q^2}{h^3} \frac{\partial h}{\partial x} + g \frac{\partial \zeta}{\partial x} = 0 \quad (\text{D.5})$$

We assume that the artificial viscosity  $\Psi$  is proportional to the numerical error of the gradient term.

### Based on potential energy

Looking to square root of the potential energy

$$Err \left( \sqrt{gh} \right) = \sqrt{gh} - \sqrt{\bar{h}} \approx \quad (\text{D.6})$$

$$\approx \sqrt{g \left( \bar{h} + \frac{1}{8} \Delta x^2 \frac{\partial^2 \bar{h}}{\partial x^2} \right)} - \sqrt{\bar{h}} = \quad (\text{D.7})$$

$$= \sqrt{g \bar{h} \left( 1 + \frac{1}{8\bar{h}} \Delta x^2 \frac{\partial^2 \bar{h}}{\partial x^2} \right)} - \sqrt{g \bar{h}} \approx \quad (\text{D.8})$$

$$\approx \sqrt{g \bar{h}} \left( 1 + \frac{1}{16\bar{h}} \Delta x^2 \frac{\partial^2 \bar{h}}{\partial x^2} \right) - \sqrt{g \bar{h}} = \quad (\text{D.9})$$

$$= \frac{1}{16} \Delta x^2 \sqrt{\frac{g}{\bar{h}} \frac{\partial^2 \bar{h}}{\partial x^2}} \quad (\text{D.10})$$

Because  $\partial^2 z_b / \partial x^2$  is negligible, due to the regularization of the bedlevel, we get:

$$Err \left( \sqrt{gh} \right) = \frac{1}{16} \Delta x^2 \sqrt{\frac{g}{\bar{h}} \frac{\partial^2 \zeta}{\partial x^2}} \quad (\text{D.11})$$

$$\Rightarrow \frac{1}{16} \Delta \xi^2 \sqrt{\frac{g}{\bar{h}} \frac{\partial^2 \zeta}{\partial \xi^2}}, \quad [\text{m s}^{-1}]. \quad (\text{D.12})$$

### Based on kinetic energy

Looking to square root of the kinetic energy:  $\sqrt{u^2/2} = \frac{1}{2}\sqrt{2}|u| = \frac{1}{2}\sqrt{2}|q/h|$ :

$$Err \left( \frac{1}{2} \sqrt{2} \frac{\bar{q}}{\bar{h}} \right) = \frac{1}{2} \sqrt{2} \left( \frac{\bar{q}}{\bar{h}} - \frac{\bar{q}}{\bar{h}} \right) \approx \frac{1}{2} \sqrt{2} \left( \frac{\bar{q} + \frac{1}{8} \Delta x^2 \frac{\partial^2 \bar{q}}{\partial x^2}}{\bar{h} + \frac{1}{8} \Delta x^2 \frac{\partial^2 \bar{h}}{\partial x^2}} - \frac{\bar{q}}{\bar{h}} \right) = \quad (\text{D.13})$$

$$= \frac{1}{2} \sqrt{2} \left( \frac{\bar{q}}{\bar{h}} \frac{1 + \frac{1}{8} \Delta x^2 \frac{1}{\bar{q}} \frac{\partial^2 \bar{q}}{\partial x^2}}{1 + \frac{1}{8} \Delta x^2 \frac{1}{\bar{h}} \frac{\partial^2 \bar{h}}{\partial x^2}} - \frac{\bar{q}}{\bar{h}} \right) \approx \quad (\text{D.14})$$

$$\approx \frac{1}{2} \sqrt{2} \left( \frac{\bar{q}}{\bar{h}} \left( 1 + \frac{1}{8} \Delta x^2 \frac{1}{\bar{q}} \frac{\partial^2 \bar{q}}{\partial x^2} \right) \left( 1 - \frac{1}{8} \Delta x^2 \frac{1}{\bar{h}} \frac{\partial^2 \bar{h}}{\partial x^2} \right) - \frac{\bar{q}}{\bar{h}} \right) \approx \quad (\text{D.15})$$

$$\approx \frac{1}{2} \sqrt{2} \left( \frac{1}{8} \Delta x^2 \frac{1}{\bar{h}} \frac{\partial^2 \bar{q}}{\partial x^2} - \frac{1}{8} \Delta x^2 \frac{\bar{q}}{\bar{h}^2} \frac{\partial^2 \bar{h}}{\partial x^2} \right) \quad (\text{D.16})$$

$$\Rightarrow \frac{1}{16} \sqrt{2} \Delta \xi^2 \left( \frac{1}{\bar{h}} \frac{\partial^2 \bar{q}}{\partial \xi^2} - \frac{\bar{q}}{\bar{h}^2} \frac{\partial^2 \bar{h}}{\partial \xi^2} \right), \quad [\text{m s}^{-1}]. \quad (\text{D.17})$$

The error function for artificial viscosity  $Err_\Psi$  reads (comparable with [Borsboom \(2001, eq. 42\)](#)):

$$Err_\Psi = \Delta \xi \bar{x}_\xi \left( \frac{1}{16} \sqrt{\frac{g}{\bar{h}}} |D_\xi(\bar{\zeta})| + \frac{\sqrt{2}}{16} \left| \frac{1}{\bar{h}} D_\xi(\bar{q}) - \frac{\bar{q}}{\bar{h}^2} D_\xi(\bar{h}) \right| \right), \quad [\text{m}^2 \text{s}^{-1}] \quad (\text{D.18})$$

with  $D_\xi$  defined as (Borsboom, 2001, eq. 35):

$$D_\xi = \Delta\xi^2 \frac{\partial^2 u}{\partial\xi^2} \approx u_{i-1} - 2u_i + u_{i+1}, \quad u \in \{q, h, \zeta\} \quad (\text{D.19})$$

# E Linearization in time

## E.1 Viscosity term

The viscosity term read:

$$\int_{x_{i-\frac{1}{2}}}^{x_{i+\frac{1}{2}}} \frac{\partial}{\partial x} \left( \nu h \frac{\partial(q/h)}{\partial x} \right) dx = \nu \left( \frac{\partial q}{\partial x} - \frac{q}{h} \frac{\partial h}{\partial x} \right) \Big|_{x_{i+\frac{1}{2}}} - \nu \left( \frac{\partial q}{\partial x} - \frac{q}{h} \frac{\partial h}{\partial x} \right) \Big|_{x_{i-\frac{1}{2}}} \quad (\text{E.1})$$

Linearization of the viscosity term at  $x_{i+\frac{1}{2}}$  read, where  $\Delta h^{n+1,p+1} = \Delta h$  and  $\Delta q^{n+1,p+1} = \Delta q$ :

$$\nu h \frac{\partial(q/h)}{\partial x} \Big|^{n+\theta,p+1} = \nu \left( \frac{\partial q}{\partial x} - \frac{q}{h} \frac{\partial h}{\partial x} \right) \Big|^{n+\theta,p+1} \approx \quad (\text{E.2})$$

$$\approx \nu \frac{\partial}{\partial x} (q^{n+\theta,p} + \theta \Delta q) - \nu \frac{q^{n+\theta,p} + \theta \Delta q}{h^{n+\theta,p} + \theta \Delta h} \frac{\partial}{\partial x} (h^{n+\theta,p} + \theta \Delta h) \approx \quad (\text{E.3})$$

with

$$\frac{q^{n+\theta,p} + \theta \Delta q}{h^{n+\theta,p} + \theta \Delta h} \approx \frac{q^{n+\theta,p} + \theta \Delta q}{h^{n+\theta,p}} \left( 1 - \frac{\theta \Delta h}{h^{n+\theta,p}} + \left( \frac{\theta \Delta h}{h^{n+\theta,p}} \right)^2 - \left( \frac{\theta \Delta h}{h^{n+\theta,p}} \right)^3 + \dots \right) = \quad (\text{E.4})$$

$$= \frac{q^{n+\theta,p}}{h^{n+\theta,p}} - \frac{q^{n+\theta,p}}{(h^{n+\theta,p})^2} \theta \Delta h + \frac{1}{h^{n+\theta,p}} \theta \Delta q + O(\Delta q \Delta h, (\Delta h)^2) \quad (\text{E.5})$$

leaving out the terms of  $O(\Delta q \Delta h, (\Delta h)^2)$ , yields:

$$\nu h \frac{\partial(q/h)}{\partial x} \Big|^{n+\theta,p+1} = \nu \left( \frac{\partial q}{\partial x} - \frac{q}{h} \frac{\partial h}{\partial x} \right) \Big|^{n+\theta,p+1} \approx \quad (\text{E.6})$$

$$\approx \nu \frac{\partial}{\partial x} (q^{n+\theta,p} + \theta \Delta q) + \quad (\text{E.7})$$

$$- \nu \left( \frac{q^{n+\theta,p}}{h^{n+\theta,p}} + \frac{1}{h^{n+\theta,p}} \theta \Delta q - \frac{q^{n+\theta,p}}{(h^{n+\theta,p})^2} \theta \Delta h \right) \frac{\partial}{\partial x} (h^{n+\theta,p} + \theta \Delta h) = \quad (\text{E.8})$$

$$= \nu \frac{\partial q^{n+\theta,p}}{\partial x} + \nu \frac{\partial}{\partial x} \theta \Delta q + \quad (\text{E.9})$$

$$- \nu \frac{q^{n+\theta,p}}{h^{n+\theta,p}} \frac{\partial h^{n+\theta,p}}{\partial x} - \nu \frac{q^{n+\theta,p}}{h^{n+\theta,p}} \frac{\partial}{\partial x} \theta \Delta h - \frac{1}{h^{n+\theta,p}} \frac{\partial h^{n+\theta,p}}{\partial x} \theta \Delta q + \frac{q^{n+\theta,p}}{(h^{n+\theta,p})^2} \frac{\partial h^{n+\theta,p}}{\partial x} \theta \Delta h \quad (\text{E.10})$$

rearranged

$$\nu h \frac{\partial(q/h)}{\partial x} \Big|^{n+\theta,p+1} = \nu \left( \frac{\partial q}{\partial x} - \frac{q}{h} \frac{\partial h}{\partial x} \right) \Big|^{n+\theta,p+1} \approx \quad (\text{E.11})$$

$$= \nu \frac{\partial q^{n+\theta,p}}{\partial x} - \nu \frac{q^{n+\theta,p}}{h^{n+\theta,p}} \frac{\partial h^{n+\theta,p}}{\partial x} + \quad (\text{E.12})$$

$$+ \nu \theta \frac{\partial \Delta q}{\partial x} - \nu \theta \frac{1}{h^{n+\theta,p}} \frac{\partial h^{n+\theta,p}}{\partial x} \Delta q + \nu \theta \frac{q^{n+\theta,p}}{(h^{n+\theta,p})^2} \frac{\partial h^{n+\theta,p}}{\partial x} \Delta h - \nu \theta \frac{q^{n+\theta,p}}{h^{n+\theta,p}} \frac{\partial \Delta h}{\partial x} \quad (\text{E.13})$$

# F Regularization of a two dimensional given function $u_{giv}$

The regularization function read, based on [Borsboom \(1998, eq. 6\)](#):

$$\tilde{u} - \nabla \cdot \Psi \nabla \tilde{u} = u_{giv}, \quad \Psi = c_\Psi (\Delta x^2 + \Delta y^2) E, \quad (\text{F.1})$$

with  $\Psi$  the artificial viscosity and defined as:

$$\Psi = \begin{pmatrix} \Psi_{11} & \Psi_{12} \\ \Psi_{21} & \Psi_{22} \end{pmatrix} \quad (\text{F.2})$$

where

$u_{giv}$	a given function, ex. bathymetry, viscosity, $\dots$ , $[\cdot]$ .
$\tilde{u}$	Regularized/Smoothed function of $u_{giv}$ , $[\cdot]$ .
$\Psi$	(artificial) smoothing constant, $[\text{m}^2]$
$\Delta x, \Delta y$	Space discretization, $\Delta x_i = x_{i+\frac{1}{2}} - x_{i-\frac{1}{2}}$ and $\Delta y_j = y_{j+\frac{1}{2}} - y_{j-\frac{1}{2}}$ , $[\text{m}]$
$c_\Psi$	Smoothing factor (set by user), $[1/\cdot]$
$E$	Error function, $[\cdot]$

First the discretization of [equation \(F.1\)](#) is discussed and second the determination of the artificial smoothing coefficient  $\Psi$ .

Notation agreements:

$u$	Non-regularized/non-smoothed function, to be determined numerically.
$\tilde{u}$	Regularized/smoothed function, denoted by the wavy line.
$\bar{u}$	Piecewise linear function, denoted by the bar.
$u_i$	Value of the numerical value at point $x_i$ .

## F.1 Discretization

The finite volume approach of this equation read:

$$\int_{\Omega} \tilde{u} d\omega - \int_{\Omega} \nabla \cdot \Psi \nabla \tilde{u} d\omega = \int_{\Omega} u_{giv} d\omega \quad (\text{F.3})$$

## Integration of the first term

The discretization of first term of equation (F.3) read (see for the coefficients Figure 7.2):

$$\begin{aligned} \int_{\Omega} u d\omega &\approx \Delta x \Delta y \left( \frac{1}{64} u_{i-1,j-1} + \frac{6}{64} u_{i,j-1} + \frac{1}{64} u_{i+1,j-1} + \right. \\ &+ \frac{6}{64} u_{i-1,j} + \frac{36}{64} u_{i,j} + \frac{6}{64} u_{i+1,j} + \\ &\left. + \frac{1}{64} u_{i-1,j+1} + \frac{6}{64} u_{i,j+1} + \frac{1}{64} u_{i+1,j+1} \right) \end{aligned} \quad (\text{F.4})$$

## Integration of the second term

Integration of the second term:

$$\int_{\Omega} \nabla \cdot \Psi \nabla \tilde{u} d\omega = \int_{\Gamma} \Psi \nabla \tilde{u} \cdot \hat{\mathbf{n}} ds \approx \quad (\text{F.5})$$

$$\begin{aligned} &\approx \frac{1}{2\Delta y} \left( \Psi_{11} \frac{\partial \tilde{u}}{\partial x} + \Psi_{12} \frac{\partial \tilde{u}}{\partial y} \right) \Big|_{i+\frac{1}{2}, j-\frac{1}{4}} + \frac{1}{2\Delta y} \left( \Psi_{11} \frac{\partial \tilde{u}}{\partial x} + \Psi_{12} \frac{\partial \tilde{u}}{\partial y} \right) \Big|_{i+\frac{1}{2}, j+\frac{1}{4}} + \end{aligned} \quad (\text{F.6})$$

$$\begin{aligned} &+ \frac{1}{2\Delta x} \left( \Psi_{21} \frac{\partial \tilde{u}}{\partial x} + \Psi_{22} \frac{\partial \tilde{u}}{\partial y} \right) \Big|_{i-\frac{1}{4}, j+\frac{1}{2}} + \frac{1}{2\Delta x} \left( \Psi_{21} \frac{\partial \tilde{u}}{\partial x} + \Psi_{22} \frac{\partial \tilde{u}}{\partial y} \right) \Big|_{i+\frac{1}{4}, j+\frac{1}{2}} + \end{aligned} \quad (\text{F.7})$$

$$\begin{aligned} &- \frac{1}{2\Delta y} \left( \Psi_{11} \frac{\partial \tilde{u}}{\partial x} + \Psi_{12} \frac{\partial \tilde{u}}{\partial y} \right) \Big|_{i-\frac{1}{2}, j-\frac{1}{4}} - \frac{1}{2\Delta y} \left( \Psi_{11} \frac{\partial \tilde{u}}{\partial x} + \Psi_{12} \frac{\partial \tilde{u}}{\partial y} \right) \Big|_{i-\frac{1}{2}, j+\frac{1}{4}} \end{aligned} \quad (\text{F.8})$$

$$\begin{aligned} &- \frac{1}{2\Delta x} \left( \Psi_{21} \frac{\partial \tilde{u}}{\partial x} + \Psi_{22} \frac{\partial \tilde{u}}{\partial y} \right) \Big|_{i-\frac{1}{4}, j-\frac{1}{2}} - \frac{1}{2\Delta x} \left( \Psi_{21} \frac{\partial \tilde{u}}{\partial x} + \Psi_{22} \frac{\partial \tilde{u}}{\partial y} \right) \Big|_{i+\frac{1}{4}, j-\frac{1}{2}} \end{aligned} \quad (\text{F.9})$$

Define the components of  $\Psi$  at different locations with  $(\mu, \nu) \in \{1, 2\}$  as

$$\bar{\Psi}_{\mu\nu} \Big|_{i+\frac{1}{2}, j+\frac{1}{4}} = \frac{1}{8} \left( 3\Psi_{\mu\nu} \Big|_{i,j} + 3\Psi_{\mu\nu} \Big|_{i+1,j} + \Psi_{\mu\nu} \Big|_{i+1,j+1} + \Psi_{\mu\nu} \Big|_{i,j+1} \right) \quad (\text{F.10})$$

and define the partial differentials as

$$\frac{\partial u}{\partial x} \Big|_{i+\frac{1}{2}, j+\frac{1}{4}} = \frac{1}{4} \left( 3 \frac{u_{i+1,j} - u_{i,j}}{\Delta x_{i+\frac{1}{2},j}} + \frac{u_{i+1,j+1} - u_{i,j+1}}{\Delta x_{i+\frac{1}{2},j+1}} \right) \quad (\text{F.11})$$

$$\frac{\partial u}{\partial y} \Big|_{i+\frac{1}{2}, j+\frac{1}{4}} = \frac{1}{2} \left( \frac{u_{i,j+1} - u_{i,j}}{\Delta y_{i,j+\frac{1}{2}}} + \frac{u_{i+1,j+1} - u_{i+1,j}}{\Delta y_{i+1,j+\frac{1}{2}}} \right) \quad (\text{F.12})$$

In case the artificial viscosity is symmetric ( $\Psi_{12} = \Psi_{21} = 0$ ) it reads:

$$\int_{\Omega} \nabla \cdot \Psi \nabla \tilde{u} d\omega = \int_{\Gamma} \Psi \nabla \tilde{u} \cdot \hat{\mathbf{n}} ds \approx \quad (\text{F.13})$$

$$\approx \frac{1}{2\Delta y} \left( \Psi_{11} \frac{\partial \tilde{u}}{\partial x} \right) \Big|_{i+\frac{1}{2}, j-\frac{1}{4}} + \frac{1}{2\Delta y} \left( \Psi_{11} \frac{\partial \tilde{u}}{\partial x} \right) \Big|_{i+\frac{1}{2}, j+\frac{1}{4}} + \quad (\text{F.14})$$

$$+ \frac{1}{2\Delta x} \left( \Psi_{22} \frac{\partial \tilde{u}}{\partial y} \right) \Big|_{i-\frac{1}{4}, j+\frac{1}{2}} + \frac{1}{2\Delta x} \left( \Psi_{22} \frac{\partial \tilde{u}}{\partial y} \right) \Big|_{i+\frac{1}{4}, j+\frac{1}{2}} + \quad (\text{F.15})$$

$$- \frac{1}{2\Delta y} \left( \Psi_{11} \frac{\partial \tilde{u}}{\partial x} \right) \Big|_{i-\frac{1}{2}, j-\frac{1}{4}} - \frac{1}{2\Delta y} \left( \Psi_{11} \frac{\partial \tilde{u}}{\partial x} \right) \Big|_{i-\frac{1}{2}, j+\frac{1}{4}} \quad (\text{F.16})$$

$$- \frac{1}{2\Delta x} \left( \Psi_{22} \frac{\partial \tilde{u}}{\partial y} \right) \Big|_{i-\frac{1}{4}, j-\frac{1}{2}} - \frac{1}{2\Delta x} \left( \Psi_{22} \frac{\partial \tilde{u}}{\partial y} \right) \Big|_{i+\frac{1}{4}, j-\frac{1}{2}} \quad (\text{F.17})$$

In case the artificial viscosity is isotropic it reads:

$$\Psi = \begin{pmatrix} \Psi & 0 \\ 0 & \Psi \end{pmatrix} \quad (\text{F.18})$$

(isotropic,  $\Psi_{11} = \Psi_{22} = \Psi$  and  $\Psi_{12} = \Psi_{21} = 0$ ).

The integration of the second term will reduce to:

$$\int_{\Omega} \nabla \cdot \Psi \nabla \tilde{u} d\omega = \int_{\Gamma} \Psi \nabla \tilde{u} \cdot \hat{\mathbf{n}} ds = \Psi \int_{i-\frac{1}{2}}^{i+\frac{1}{2}} \int_{j-\frac{1}{2}}^{j+\frac{1}{2}} \nabla \tilde{u} \cdot \hat{\mathbf{n}} dy dx \approx \quad (\text{F.19})$$

$$\approx \Psi \left( \frac{1}{2\Delta y} \frac{\partial \tilde{u}}{\partial x} \Big|_{i+\frac{1}{2}, j-\frac{1}{4}} + \frac{1}{2\Delta y} \frac{\partial \tilde{u}}{\partial x} \Big|_{i+\frac{1}{2}, j+\frac{1}{4}} + \quad (\text{F.20}) \right.$$

$$+ \frac{1}{2\Delta x} \frac{\partial \tilde{u}}{\partial y} \Big|_{i-\frac{1}{4}, j+\frac{1}{2}} + \frac{1}{2\Delta x} \frac{\partial \tilde{u}}{\partial y} \Big|_{i+\frac{1}{4}, j+\frac{1}{2}} + \quad (\text{F.21})$$

$$- \frac{1}{2\Delta y} \frac{\partial \tilde{u}}{\partial x} \Big|_{i-\frac{1}{2}, j-\frac{1}{4}} - \frac{1}{2\Delta y} \frac{\partial \tilde{u}}{\partial x} \Big|_{i-\frac{1}{2}, j+\frac{1}{4}} \quad (\text{F.22})$$

$$\left. - \frac{1}{2\Delta x} \frac{\partial \tilde{u}}{\partial y} \Big|_{i-\frac{1}{4}, j-\frac{1}{2}} - \frac{1}{2\Delta x} \frac{\partial \tilde{u}}{\partial y} \Big|_{i+\frac{1}{4}, j-\frac{1}{2}} \right) \quad (\text{F.23})$$

## Integration of right hand side

For the integration of the right hand side we could use a smaller integration step size, to incorporate the sub-grid scale effects.

## F.2 Determination of artificial smoothing coefficient $\Psi$

The artificial smoothing coefficient (equation (F.1)) is dependent on the second derivative of given function  $u_{giv}$  (Borsboom, 1998, eq. 8). **Assuming** that  $c_E$  is constant over the whole two dimensional area, thus isotropic.

**TODO F.1:** Check next equations

**TODO**

$$\begin{aligned} & \left( \frac{1}{64} E_{i-1,j-1} + \frac{6}{64} E_{i,j-1} + \frac{1}{64} E_{i+1,j-1} + \right. \\ & + \frac{6}{64} E_{i-1,j} + \frac{36}{64} E_{i,j} + \frac{6}{64} E_{i+1,j} + \\ & + \frac{1}{64} E_{i-1,j+1} + \frac{6}{64} E_{i,j+1} + \frac{1}{64} E_{i+1,j+1} \Big) + \\ & c_E \left( \frac{1}{2\Delta y} \frac{\partial \tilde{u}}{\partial x} \Big|_{i+\frac{1}{2},j-\frac{1}{4}} + \frac{1}{2\Delta y} \frac{\partial \tilde{u}}{\partial x} \Big|_{i+\frac{1}{2},j+\frac{1}{4}} + \right. \end{aligned} \quad (\text{F.24})$$

$$+ \frac{1}{2\Delta x} \frac{\partial \tilde{u}}{\partial y} \Big|_{i-\frac{1}{4},j+\frac{1}{2}} + \frac{1}{2\Delta x} \frac{\partial \tilde{u}}{\partial y} \Big|_{i+\frac{1}{4},j+\frac{1}{2}} + \quad (\text{F.25})$$

$$- \frac{1}{2\Delta y} \frac{\partial \tilde{u}}{\partial x} \Big|_{i-\frac{1}{2},j-\frac{1}{4}} - \frac{1}{2\Delta y} \frac{\partial \tilde{u}}{\partial x} \Big|_{i-\frac{1}{2},j+\frac{1}{4}} \\ - \frac{1}{2\Delta x} \frac{\partial \tilde{u}}{\partial y} \Big|_{i-\frac{1}{4},j-\frac{1}{2}} - \frac{1}{2\Delta x} \frac{\partial \tilde{u}}{\partial y} \Big|_{i+\frac{1}{4},j-\frac{1}{2}} \Big) = \quad (\text{F.26})$$

$$= \frac{1}{\Delta x \Delta y} \int_{j-\frac{1}{2}}^{j+\frac{1}{2}} \int_{i-\frac{1}{2}}^{i+\frac{1}{2}} |D| dx dy \quad (\text{F.27})$$

with (Borsboom, 1998, eq. 2)

$$D = \Delta x^2 \frac{\partial^2 u_{giv}}{\partial x^2} + \Delta y^2 \frac{\partial^2 u_{giv}}{\partial y^2} \quad (\text{F.28})$$

and

$$\begin{aligned} c_E &= \max \left( c_\Psi \Delta x^2 \frac{\partial^2 u_{giv}}{\partial x^2}, c_\Psi \Delta y^2 \frac{\partial^2 u_{giv}}{\partial y^2} \right) \\ &= \max \left( c_\Psi \left| u_{giv_{i-1,j}} - 2u_{giv_{i,j}} + u_{giv_{i+1,j}} \right|, c_\Psi \left| u_{giv_{i,j-1}} - 2u_{giv_{i,j}} + u_{giv_{i,j+1}} \right| \right), \forall i \end{aligned} \quad (\text{F.29})$$

The right hand side is approximated by:

$$\begin{aligned} & \frac{1}{\Delta x \Delta y} \int_{j-\frac{1}{2}}^{j+\frac{1}{2}} \int_{i-\frac{1}{2}}^{i+\frac{1}{2}} |D| dx dy = \\ & = \frac{1}{64} |D|_{i-1,j-1} + \frac{6}{64} |D|_{i,j-1} + \frac{1}{64} |D|_{i+1,j-1} + \\ & + \frac{6}{64} |D|_{i-1,j} + \frac{36}{64} |D|_{i,j} + \frac{6}{64} |D|_{i+1,j} + \\ & + \frac{1}{64} |D|_{i-1,j+1} + \frac{6}{64} |D|_{i,j+1} + \frac{1}{64} |D|_{i+1,j+1} \end{aligned} \quad (\text{F.30})$$

Now system [equation \(F.27\)](#) can be solved and  $\Psi$  is set to:

$$\Psi = c_\Psi (\Delta x^2 + \Delta y^2) E \quad (\text{F.31})$$

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