Integrated 2D model of rainfall-runoff and 1D model of sewer network

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Introduction

A new integrated 1D/2D model to compute the interaction between surface runoff and sewer network in urban areas is presented. Both models are based on the Saint-Venant shallow water equations. The scope is the development of a tool capable of computing the whole processes that take place in urban drainage, from rainfall runoff generation to flow in sewer network and final affection to the receiving environment.

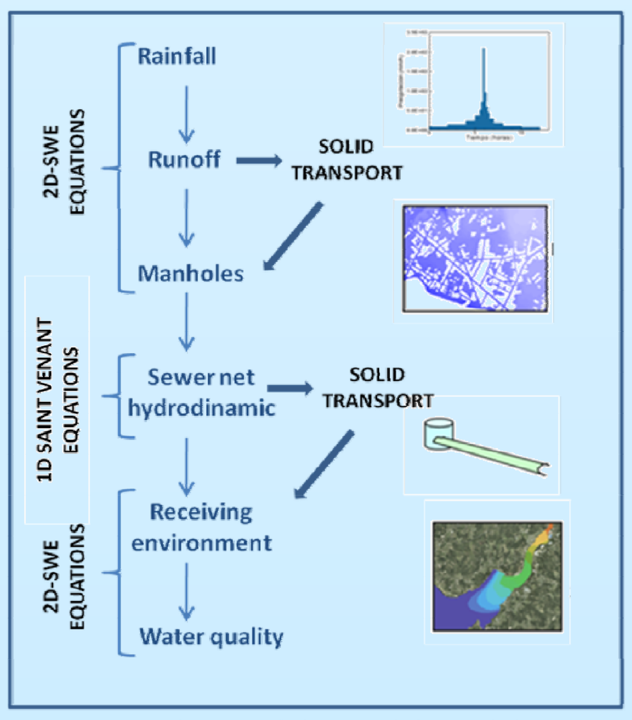


Figure 1. Scheme of the model capabilities

Model description

This model is based on the interaction of a 1D model and a 2D model. The 2D model computes water and pollutant flows and water quality parameters. The 1D model simulates water and solid flows in sewer networks and inflows and outflows at manholes. Coupling of both models takes place via manholes.

•2D model

The 2D model is structured in several modules. The hydrodynamic and turbulence modules solve the 2D shallow water Saint Venant equations, obtaining velocity and water depth fields. The Sediment transport module computes the entrainment, transport and deposition of solids from the hydrodynamic results.

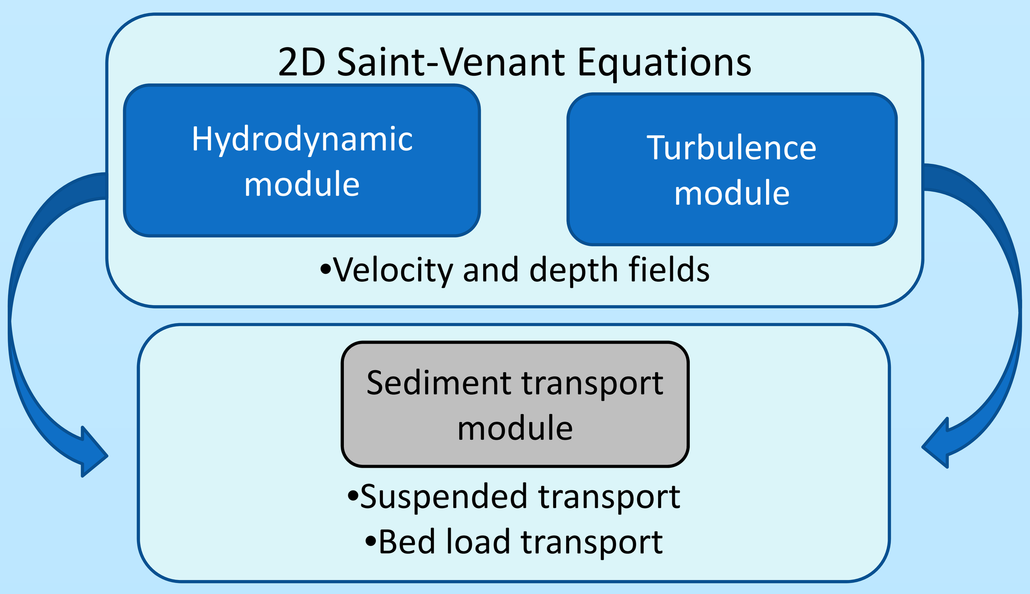


Figure 2. Structure of the 2D model

The St. Venant equations are solved with an explicit Godunov finite volume scheme which are very robust and accurate for modelling shallow flows. A detailed description of the 2D model can be found in (Cea et al., 2007)

This model has been validated and applied to rainfall-runoff, sediment transport and water quality computations (Cea et al 2010a, b), where it has proved to deal efficiently with some of the main numerical difficulties which appear in the modelling of overland flow, as are the presence of highly unsteady wet-dry fronts, the extremely small water depths, and high bed friction stresses.

•1D model

The 1D sewer flow model is based on the Saint-Venant equations and considers both free-surface and pressure flow conditions. Like the 2D model, it is divided in different modules.

Hydrodynamic module

This module solves the St.Venant equations with a Goudunov-type finite volume method, where pipes are divided in cells of width $\Delta x=L/n$. Solution in cell *i* is then calculated with the following equation:

$$U_i^{n+1} = U_i^n - \frac{\Delta t}{\Delta x}\left[F_{i+1/2}^n - F_{i-1/2}^n\right] + \Delta t\left[\left(S_o\right)_i^n + (S_f)_i^{n+1}\right]$$

$$U = \begin{pmatrix} A \\ Q \end{pmatrix} \quad F = \begin{pmatrix} Q \\ Q^2/A + I \end{pmatrix} \quad S_o = \begin{pmatrix} 0 \\ gA\,dz/dx \end{pmatrix} \quad S_f = \begin{pmatrix} 0 \\ -c_D \frac{PQ|Q|}{A^2} \end{pmatrix}$$

To compute fluxes in the interior cell edges ($F_{i+1/2}$ and $F_{i-1/2}$) the HLL formulation is used (Toro 2001)

$$F = \begin{cases} F_L & \text{if} \quad s_L < 0 \\ F^* & \text{if} \quad s_L \le 0 \le s_R \\ F_R & \text{if} \quad s_R < 0 \end{cases} \qquad F^* = \frac{s_R F_L - s_L F_R + s_L s_R (U_R - U_L)}{s_R - s_L}$$

Sub-index *L* and *R* refer to left and right cells respectively and *s* is wave speed, calculated according to (Toro,2001). Slope source terms (*So*) are treated explicitly and flow resistance source term (*Sf*) are treated implicitly for stability. Fluxes at boundary edges ($F_{1/2}$ and $F_{n+1/2}$) are calculated with specific formulation, depending on water depth at both manhole and pipe, and flow regime (subcritical or supercritical). A detailed description of the different formulation used can be found in (Sanders and Bradford, 2011)

Sediment transport module

Sediment transport is computed with an specific module following the described methodology

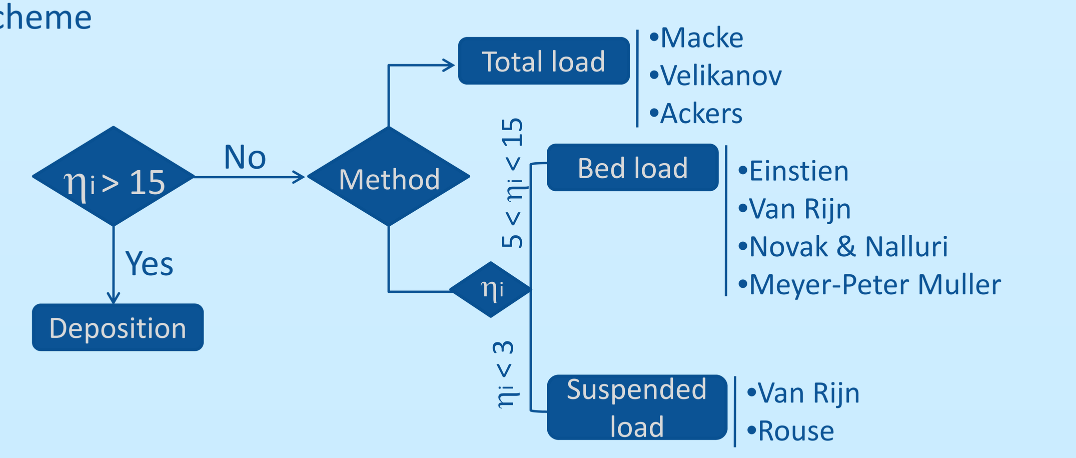
➢The **type of transport** for each sediment fraction (sub-index *i*) is determined, depending on the sedimentation parameter η_i

$$\eta_i = \frac{w_i}{\kappa u_i^*} \begin{cases} \eta_i < 3 \text{ suspenden load} \\ 5 < \eta_i < 15 \text{ bed load} \\ 15 < \eta_i \text{ deposition} \end{cases}$$

u* -> shear velocity

w -> settling velocity

➢**Potential sediment transport** (Mass pot) is computed from flow values obtained in the hydrodynamic module and sediment characteristics. Different formulae are considered as described in this scheme



➢The **available mass** is then computed, considering three different sources: intakes from junctions, transported sediment in the water and accumulated sediment in the pipe bottom.

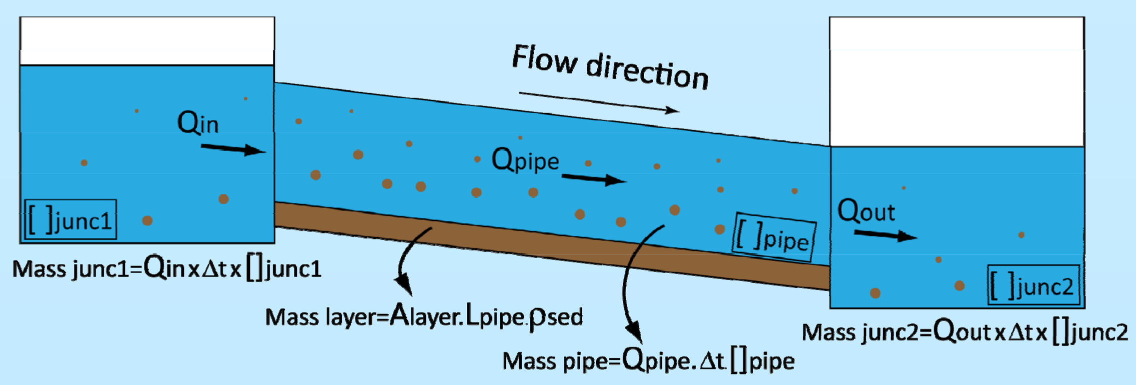


Figure 3. Mass avaliability in the different elements of the sewer network

➢**Effective transport** is calculated, according to the following criteria

- If **Mass junc + Mass pipe > Mass pot**. Flow velocities are too low to transport the available mass and **accumulation** takes place. Mass pipe* = Mass pot ;ΔMass layer= Mass pot -Mass junc-Mass pipe
- •If **Mass junc + Mass pipe < Mass pot** and **Mass junc + Mass pipe + Mass layer > Mass pot.** Sediment in the accumulated layer is **eroded** to reach potencial transport.

  Mass pipe* = Mass pot; ΔMass layer= Mass pot -Mass junc-Mass pipe
- • If **Mass junc + Mass pipe + Mass layer < Mass pot.** Transport capacity exceeds the available mass of sediment and the effective transport is limited by availability.

  Mass pipe* = Mass junc + Mass pipe + Mass layer ;Mass layer* = 0

*refers to variables in every new iteration.

➢The **new cross section** is calculated.

A layer* = Mass layer* / (L pipe * ρ sed)

➢The **composite roughness** is determined with the following equation, where sub-index *b* refers to the sediment layer and *o* to the pipe wall

$$\lambda_c = \frac{\lambda_o P_o + \lambda_b W_b}{P_o + W_b}$$

λ -> friction factor

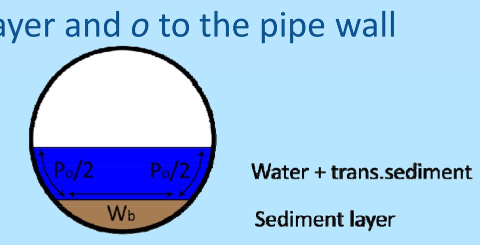


Figure 4. Pipe perimeter and layer width considered

Model linkage

Linkage between 1D and 2D models takes place through manholes, where water and pollutant mass can be both inputs and outputs. Different discharge equations are used, depending on the water level in the sewer network and on the overland flow. Description of used formulae can be found in (Chen et al., 2007).

In addition to flow dynamic linkage, both models are synchronized as each model uses different time steps.

Δt_{2D} = CFL $_{2D}$ x Area /(v $_{mod}$ x Perimeter)

Δt_{1D} = CFL $_{1D}$ x Length /(v $_{mod}$ + wave celerity)

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Model testing

In order to test the model, two simple cases were simulated. The first of them, tests the linkage and the hydrodynamic module of the 1D model. The second case tests the sediment transport module for a single pipe.

•Case 1

The first one is a simple case, consisting in a 100x25 m., idealized square basin with three sloping surfaces. The sewer net has 8 pipes and 9 manholes, and the whole net is initially dry. All the pipes have a slope of 5‰ and a Manning coefficient of 0.015 $s.m^{-1/3}$. A constant rainfall intensity of 500 mm/h is defined for the whole surface and critical water depth is imposed at the surface outlet. The outlet manhole 9 is supposed to be connected to a river, and a constant water surface elevation is imposed. No sediment transport is considered is this case. Results of the stationary state are shown in the following figures

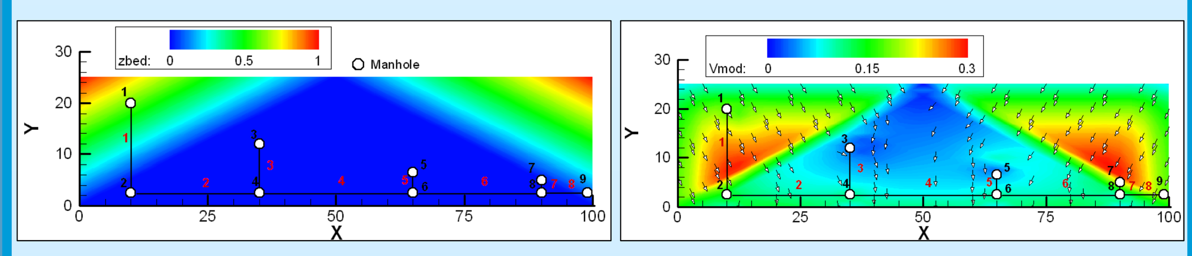
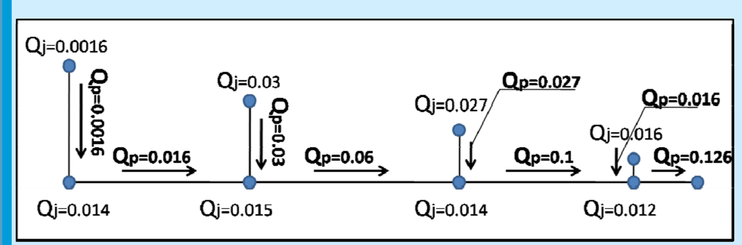


Figure 5. Basin topography in meters (left) and velocity field in m/s (right)



Pipe	Diameter (m)	Depth (cm)
1	0.25	3.6
2	0.5	8.9
3	0.25	17.5
4	0.5	17.4
5	0.25	16.1
6	0.5	23.1
7	0.25	11.5
8	0.5	26.4

Figure 6. Sewer network water discharges (m3/s) **Table 1**. Pipe diameters and water depths

Results show a decrease in water depths and deviations of flow traces near the manholes, due to inflows in the sewer network. Inflows are higher at manholes 3 and 5.

•Case 2

The second case is used to verify the sediment transport module. It consists in a single pipe of 4 meters long with a slope of 1.25%, diameter of 0.5 m and a sediment layer of 10 cm. Sediment characteristics are detailed in Table 2. A constant inflow discharge of 95 l/s is imposed and Macke formulation is used in order to compute the sediment transport

Sediment id.	Diam. (µm)	Density (T/m3)	Init. mass (kg)	Final mass (kg)
1	400	1.4	4.38	0
2	600	2.0	6.25	0
3	8500	2.6	10.84	10.84

Table 2. Sediment characteristics

Results show suspended transport for sediment type 1, bed load for type 2 and no transport for type 3, as shear stresses are lower than entrainment threshold.

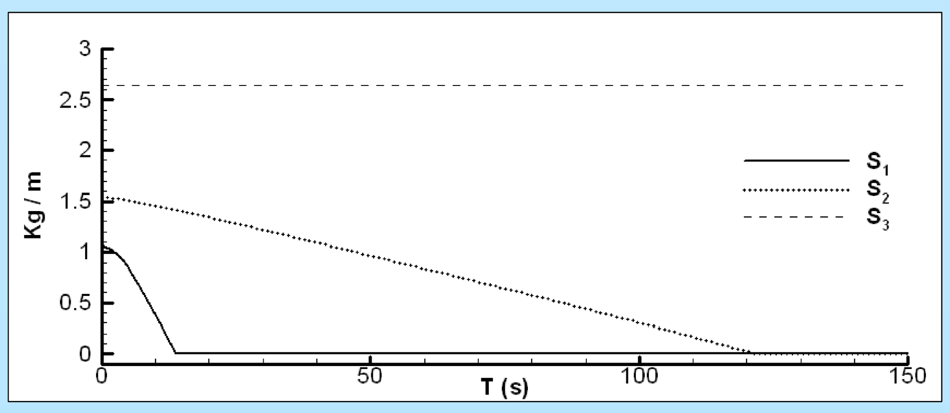


Figure 7. Sediment concentration versus time for the three considered sediment types.

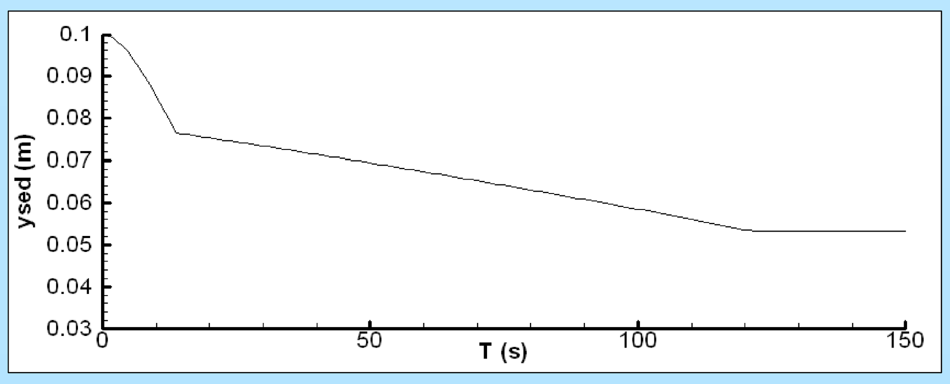


Figure 8. Sediment layer evolution

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