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 of the development of a tool capable of computing all the processes that take place in urban drainage, from rainfall generation to flow in sewer network and final affection to the receiving environment.

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 infiltrates 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 entainment, transport and deposition of solids from the hydrodynamic results.

The Saint 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 2001a, 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 unstable wet-dry fronts, the extremely small water depths, and high friction stressors.

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 four modules.

Hydrodynamic module

This module solves the Saint Venant equations with a Godunov-type finite volume method, where pipes are divided in cells of width ΔxΔh. Solution in cell j is then calculated with the following equation:

\[ U_i^{n+1} = U_i^n - \Delta t \left( \frac{F_{out} - F_{in}}{\Delta x} \right) \]

To compute flows in the interior cell edges (\( F_{in} \) and \( F_{out} \)), the HLL formulation is used (Toro 2001).

Sub-index i and j refer to left and right cells respectively and s is wave speed, calculated according to (Toro,2001). Slope source terms (Ss) are treated explicitly and flow resistance source term (Sr) are treated implicitly for stability. Fluxes at boundary edges (\( F_{out} \) and \( F_{in} \)) are calculated with specific formulations, 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 (Sandens 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 sediment transport parameter \( \psi \) as:
  \[ \psi = \frac{4.38 \times g \times y_t}{(v_s)^2} \]
  This is shear velocity
  \[ v_s = \frac{4.38 \times g \times y_t}{(u)} \]
  Deposition velocity
  \[ u \]
  Water velocity

- Potential sediment transport (Mass out) is computed from flow values obtained in the hydrodynamic module and sediment characteristics. Different formulations are described as described in this scheme.

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

- Effective transport is calculated, according to the following criteria:
  \[ u > \frac{4.38 \times g \times y_t}{(u)} \]
  Flow velocities are too low to transport the available mass and accumulation takes place.
  Mass junc = Mass pipe + Mass pot + Mass junc - Mass pipe + Mass layer
  Mass layer = Sediment in the accumulated layer is eroded to reach potential transport.
  Mass layer = 0
  \[ * \text{refers to variables in every new iteration.} \]

- The new cross section is calculated:
  \[ S_{new} = S_{old} + \Delta S \]
  \[ \Delta S = \frac{\Delta Q_{new} - \Delta Q_{old}}{\rho g} \]
  \[ \rho g \]
  Water density

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.

\[ \Delta t = C \Delta t_{max} \]

\[ C \]

\[ \Delta t_{max} \]

\[ \text{Area} \]

\[ \text{Velocity} \]

\[ \text{Polymer} \]

\[ \text{Rate} \]

\[ \text{Coefficient} \]

\[ \text{Mass} \]

\[ \text{Discharge} \]

\[ \text{Relation} \]

\[ \text{Water} \]

\[ \text{Flow} \]

\[ \text{Velocity} \]

\[ \text{Sediment} \]

Model testing

In order to test the model, two simple cases were simulated. The first one, 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 300x25 m, idealised 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 top manhole 9 is supposed to be connected to a river, and a constant water surface elevation is imposed. No sediment transport is considered in this case. Results of the stationary state are shown in the following figures:

- 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:

\[ \text{Sediment concentration versus time for the three considered sediment types.} \]

References