Evaluating SWMM capabilities to simulate closed pipe transients

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ABSTRACT

One of the most used 1D tools to model collection systems is the Storm Water Management Model (SWMM). Solving the full form of the Saint Venant equations, this model represents typical unsteady flow conditions in sewer systems. However, it may be insufficient to address fast transient flow conditions that can be present during extreme events or unscheduled operational conditions. SWMM version 5.1.013 implemented the Preissmann Slot as an alternative method to handle pressurization. To date, no studies were found analysing the applicability of SWMM to represent closed-pipe fast transient flows applying the Preissmann Slot pressurization algorithm. Therefore, the present work investigates the ability to model different fast transients conditions in SWMM under various spatial and temporal discretizations along with variations in the Preissmann Slot algorithm. Using an alternative implementation of the SLOT pressurization algorithm, along with artificial spatial discretization and routing time-steps estimated by the Courant stability condition, it is shown that SWMM is capable to perform satisfactory certain types of closed pipe transient simulations.

Keywords: Dynamic flows; Preissmann slot; Stormwater systems; SWMM; Transients; Waterhammer.

1 Introduction and objectives

The Stormwater Management Model (SWMM) is a dynamic hydrologic-hydraulic model (EPA, 2018), result of a long term development that included many researchers, users, and collaborators (Huber and Roesner, 2012). The model is often used for planning, analysis, and design related to collection systems in urban areas (Rossman, 2015). Many studies have been performed using SWMM, such as runoff quality modelling (Di Modugno et al., 2015; Tsihrintzis and Hamid, 1998), runoff quantification (Abdul-Aziz and Al-Amin, 2016; Meierdiercks et al., 2010), and, more recently, analysis of green infrastructure practices (Campisano et al., 2017; Zahmatkesh et al., 2015). Due to this variety of applications, SWMM is considered by researchers one of the most popular and successful urban water models worldwide (Niazi et al., 2017; Vasconcelos et al., 2018).

The SWMM formulation allows for the representation of unsteady free surface flow in channels and pipes. SWMM uses a link-node approach based on finite differences that solves the head in each node and the flow in each link (Roesner et al., 1988; Rossman, 2006, 2017). This solution technique does not use spatial discretization within conduits as more contemporary flow solvers; yet SWMM is suitable for the great majority of stormwater flow applications because it can properly simulate most filling processes of collection systems.

Transient flows are commonly observed in collection systems (Chaudhry, 2013). Significant changes in pressure and velocity, vibrations, reverse flows, and other situations can occur in transient flows (Thorley, 1991). In some cases, such as a pump start-up or a pipeline filling, these situations are expected and the system is designed to withstand such conditions. However, in other cases, where this situation is not planned, such as a pump failure, it may lead to unacceptable operational conditions, and even significant damage to systems.

To date, it is unknown the accuracy of SWMM to represent certain closed-pipe transient flow conditions. Furthermore, there are some limitations posed by the current lack of boundary conditions in SWMM that could represent conditions such as one-way tank, hydropneumatic tanks, pressure-relief valves, and other junctions that are present in other systems that are subject to fast transients. However, it is believe that there is a possibility of improving SWMM by adding a wider range of junctions that represent transient protective devices within SWMM.

In this context, the present work aims to evaluate the accuracy and potential limitations of SWMM 5.1.013 to represent cases of transient flows through a comparison with available analytical solutions and a benchmark model. The first case analysed is a fast transient corresponding to a sudden closure of a downstream valve presented in Wylie and Streeter (1993) and the second case is a type of fast transient resulting from a sudden pipeline flow start-up.

2 Methods

2.1 SWMM formulation

SWMM uses the Saint Venant equations to solve the unsteady free surface flow through a network of links and nodes (EPA, 2018). These equations form a system of partial differential equations which represent the unsteady open-channel flows (Sturm, 2001) based on the conservation of mass (Eq. 1a) and linear momentum (Eq. 1b). By default, SWMM solves these equations using a link-node approach, computing the flow at each link and the head in each node (Roesner et al., 1988; Rossman, 2006).

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{1a}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2 / A)}{\partial x} + gA\frac{\partial H}{\partial x} + gAS_f + gAh_L = 0 \tag{1b}$$

where A denotes cross-sectional area; t denotes time; Q denotes flow rate; x denotes distance; H denotes the hydraulic head of water in the conduit; g denotes gravity; h_L denotes the local energy loss per unit length of conduit; and S_f denotes the friction slope, which is implemented with the Manning equation (Rossman, 2006).

This default modelling approach in SWMM does not employ discretization within conduits. In some highly dynamic situations, such as pressurization of conduits, pressure surges, and pipe-filling bores, artificial spatial discretization along the full form of the Saint Venant equations brings significant improvements in SWMM results (Pachaly et al., 2020, 2019; Ridgway and Kumpula, 2007; Vasconcelos et al., 2018). Artificial spatial discretization is implemented by placing dummy nodes between actual nodes, forcing SWMM to solve the Saint Venant equations at various locations within a conduit. Adding more nodes may have a significant impact in the computational time to perform a single simulation since there are more nodes and links to be solved at each time-step (Pachaly et al., 2020, 2019) and a smaller routing time-step may be required to maintain the stability and flow continuity (Vasconcelos et al., 2018).

When the water level at a node exceeds the crown of the highest conduit connected to a SWMM junction, pressurization occurs (Rossman, 2006, 2017). The latest version of SWMM introduced a pressurization algorithm based on the Preissmann Slot (EPA, 2018). This technique uses a narrow and vertical slot over each pipe, eliminating the need to switch equations and allowing the use of the Saint Venant equations throughout the entire simulation (Cunge et al., 1980). SWMM uses a formula based on the Sjöberg slot correction (EPA, 2018) to gradually change the slot width when the flow depth is greater than 98.5% of link diameter. For the ratio of hydraulic head and pipe diameter (H/D) greater than 1.78, the slot width in SWMM 5.1.013 is equal to 1% of conduit diameter, which results in an acoustic wavespeed of approximately 27.8 m s^{-1} for a unitary diameter.

The Preissmann Slot method has two main deficiencies: it cannot sustain negative pressures and, for certain numerical schemes, spurious numerical oscillations are present when the flow switches to pressurized flow (Malekpour and Karney, 2015; Vasconcelos et al., 2009). In SWMM 5.1.013, due to the approach used to implement the Preissmann Slot, the acoustic wavespeed is too low to represent pressure propagation in closed pipe transients. A wider slot creates unrealistic storage that may have considerable consequences in the simulation (Malekpour and Karney, 2015), delaying the propagation of pressure pulses in closed pipe transients.

In this work, the SWMM source code was changed in order to assess the performance of the model after removing the Sjöberg slot correction and decreasing the slot width with a method based on celerity. Since the SLOT method maintains the open-channel flow condition, Eq. 2 gives the free surface or slot width (B) based on a specific celerity (c) for a known link cross-sectional area:

$$B = g\frac{A}{c^2}. \tag{2}$$

In addition to the original SWMM implementation, three values of celerity were used to set the slot width: 250 m s^{-1}, 500 m s^{-1}, and 1000 m s^{-1}, none of these with Sjöberg slot correction. The selected celerity values represent a range of wavespeeds that could potentially occur in closed pipe transients in collection systems. If there is no gas phase inside a pipe (air, H_2S), the celerity may be close to 1000 m s^{-1}. However, usually there is some gas in collection systems, therefore, celerity values of 250 m s^{-1} or 500 m s^{-1} are feasible in such scenarios (Wylie and Streeter, 1993). To date, there is no design guidelines on how to estimate celerity values in stormwater systems because the celerity values are influenced by air that might be entrained or entrapped during the filling process.

The equation used to estimate the routing time-step was based on the Courant-Friedrich-Lewy (CFL) stability condition (Courant et al., 1928). This condition (Eq. 3) states that the routing time-step (Δt) depends upon the spatial discretization (Δx) and celerity to maintain the stability in a finite-difference scheme (Chaudhry, 2008):

$$\Delta t = C_r\frac{\Delta x}{c}, \tag{3}$$

where the C_r term is called the Courant number. The choice of Δx and Δt should ensure that C_r does not depart much from unity to provide good results. Explicit solvers also require that $C_r \leq 1$ at all locations of the solution domain. However, SWMM solver is semi-implicit, so $C_r > 1$ should not crash the model.

Other modelling options in this study were adjusted as follows: The dynamic wave was selected as routing model keeping all inertial terms under all conditions and the normal flow criteria chosen was the slope and Froude number. Also, SWMM solution method uses a convergence tolerance and a maximum number of trials to verify if the solution converged. These values were changed, respectively, from 5×10^{-3} to 5×10^{-6} and from 8 to 20 because artificial spatial discretization was used. Reducing the calculation tolerance leads to more stringent convergence requirement, which is important to avoid numerical instabilities in the solution, and increasing the maximum number of trials will allow for more iterations to achieve this requirement.

3 Results and dicussions

3.1 Case 1: Instantaneous vale closure transient

Figure 1 shows a typical case of a transient caused by an instantaneous closure at a downstream end of a closed conduit. This situation may occur when there is a sudden vale gate maneuver, such as the damming of a check valve. Neglecting friction, minor losses and considering an instantaneous closing movement, when the valve is closed, velocity (*V*) is 0, a pressure wave of magnitude (ΔH) will be created at the downstream end of the pipe and it will travel upstream with the acoustic wavespeed (Chaudhry, 2013; Parmakian, 1963; Wylie and Streeter, 1993).

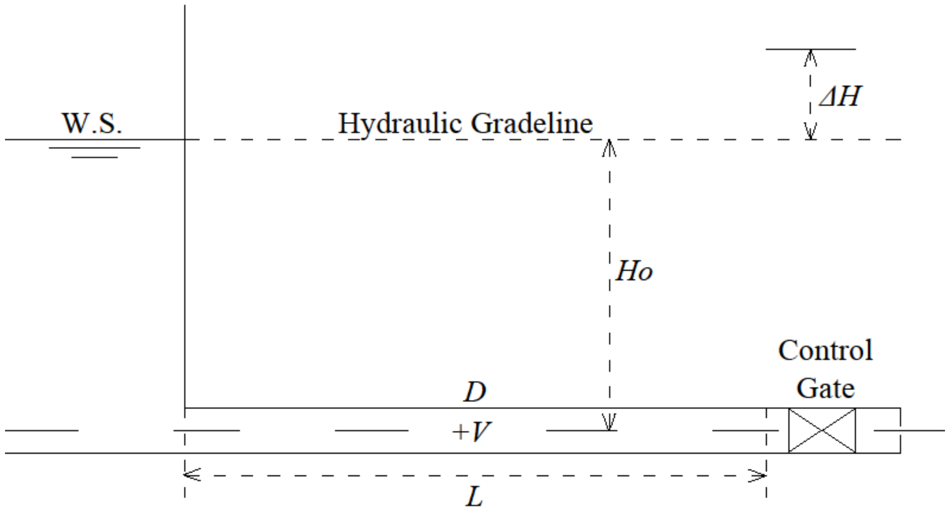

Figure 1 Instantaneous valve closure. Adapted from Wylie and Streeter (1993).

The Joukowski Eq. (Eq. 4), proposed in 1904, describes the change in pressure related to a change in flow velocity (Ghidaoui et al., 2005; Wylie and Streeter, 1993):

$$\Delta H_{anl} = \pm \frac{c}{g} \Delta V, \tag{4}$$

where ΔH_{anl} denotes instantaneous head change and ΔV denotes the instantaneous change of flow velocity. This equation states that the magnitude of the pressure wave i1s proportional to the change in the water velocity and the speed of propagation of the pressure wave (Parmakian, 1963). The analytical solution yields the maximum upsurge and this value is directly related to celerity.

In order to represent this idealized situation in SWMM, two storage units with a large area (5×10^{-3} m^2) were used. The first had a static water level (H_o) of 20 m and the second was empty. Between them, a 1000 m long, 1 m diameter pipe followed by a side circular orifice of 0.1 m height and discharge coefficient of 0.505 was set. This orifice was used to limit the flow velocity to 0.1 m s^{-1}. After the flow becomes steady, a control rule was used to rapidly close the orifice (closure time equal to Δt), representing the instantaneous valve closure.

Since changing the celerity values in SWMM will produce different head changes, the data was normalized using Eq. 5:

$$\Delta H^*_{sim} = \frac{H_{sim} - H_o}{\Delta H_{anl}}, \quad (5)$$

where ΔH^*_{sim} denotes the normalized simulated head change and H_{sim} denotes the simulated head from SWMM results. The metric selected to evaluate the model accuracy in this case is the *L2*. For discrete results, this metric measures the distance between two points on variable vectors. In this work, it evaluates the distance between the normalized SWMM values and the normalized analytical values. Eq. 6 describes the *L2* norm:

$$L2 = \sqrt{\sum (\Delta H^*_{sim} - \Delta H^*_{anl})},, \quad (5)$$

where ΔH^*_{anl} denotes the corresponding normalized analytical solution. Values closer to 0 indicate better agreement between the data analysed.

Figure 2 shows the simulation results for all pressurization algorithms. The simulations shown in these graphs were performed using a Cr of 1. The simulations using a Cr of 0.5 and 2 follow the same pattern and, for the sake of brevity, they are not shown in this work. The SWMM original implementation of the Preissmann Slot was not able to represent the analytical solution, as shown in the SLOT graph. For the modified versions of the Preissmann Slot algorithm (c250, c500, and c1000), the results show that the models without spatial discretization (Δx = 1000 m) were not able to generate satisfactory results. However, when spatial discretization is adopted, the modified versions of the Preissmann Slot provide results closer to the analytical solution, with finer discretization (Δx = 1 m) resulting in less numerical diffusion, which is in accordance with the literature (Chaudhry, 2013; Popescu, 2014). The difference between changing the celerity's values is the head change, with higher values for higher celerities, and the oscillation's periods, with longer oscillations for smaller celerities. Results in Figure 2 are not normalized; if, however, time was normalized by (*L/c*), and pressure head was normalized by ($c\ \Delta V/g$), the results would coincide across the different *c* values for a given Δx.

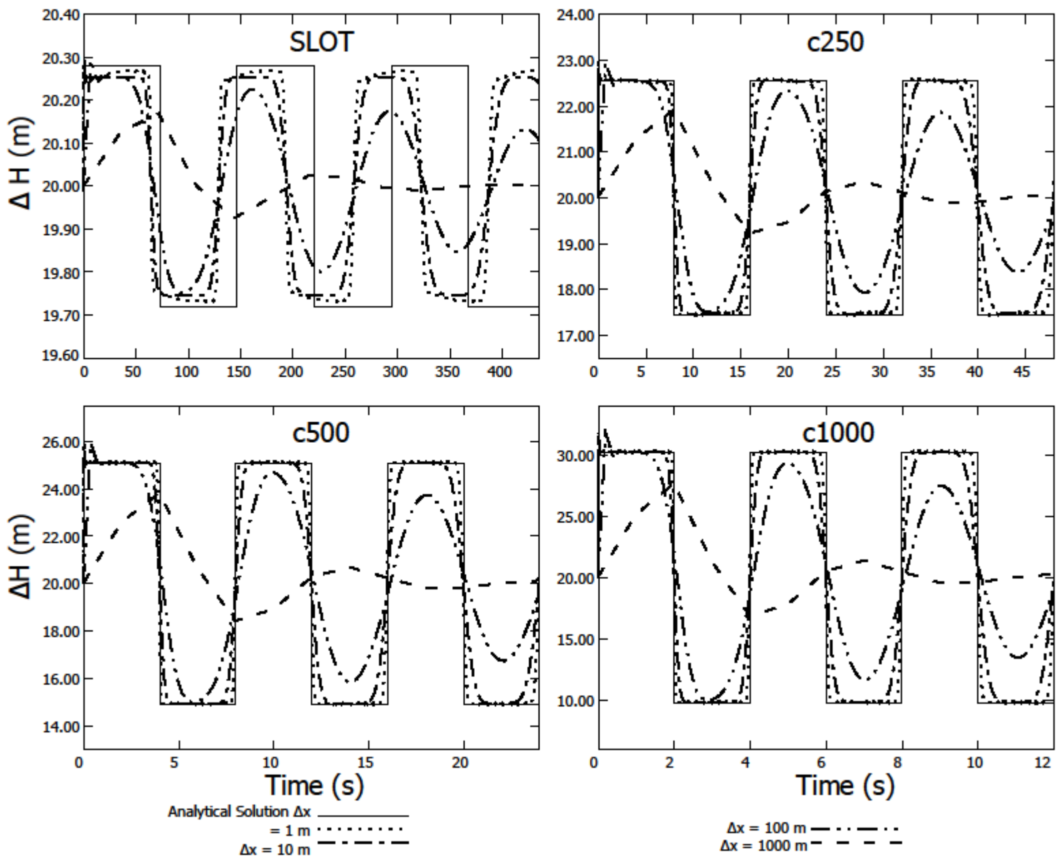

Figure 2 Simulation results for all pressurization algorithms showing the head change at the valve after the closure.

Figure 3 shows the L2 norm results. These results are consistent with the previous ones. The SLOT pressurization algorithm shows values of L2 norm in the order of 10 or greater for all discretizations. The modified versions of the Preissmann Slot (c250, c500, and c1000) reduced the L2 norm values significantly when spatial discretization is adopted. The discretization of Δx = 1 m showed values lower than 2 for the modified versions of the Preissmann Slot. Based on these results, it is possible to state that finer discretizations reduced almost exponentially the L2 norm values.

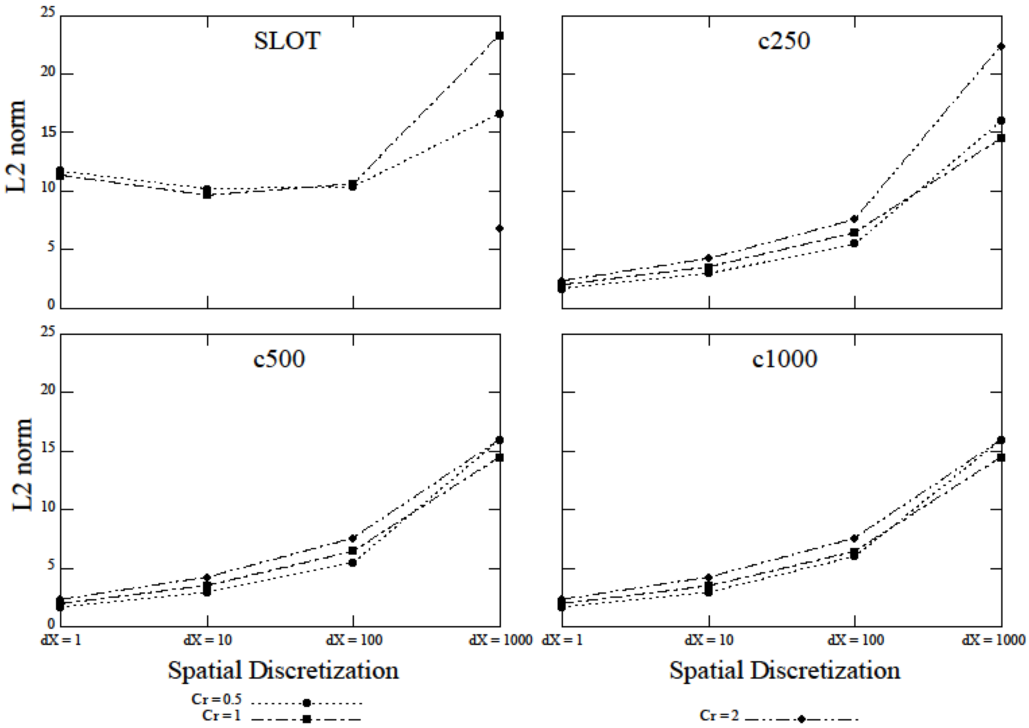

Figure 3 Simulation results for L2norm for all spatial discretization adopted and celerity values.

3.2 Case 2: Pipeline start-up

The second case considered in this work represents a pipeline with features that are typical of real-world situations. Fig. 4 shows the pipeline layout, the piezometric line prior to the valve opening, and the steady state piezometric line after the transient. The valve opening will cause a transient in the system that will propagate from upstream to downstream in cycles that will be dampened by the system's losses.

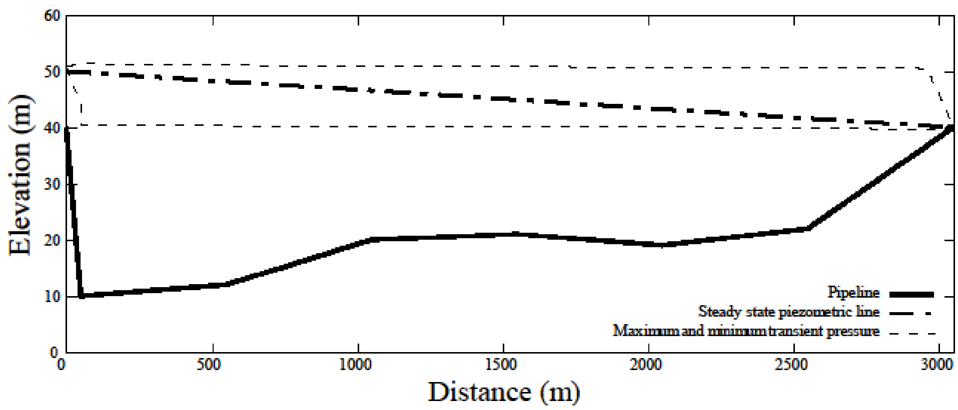

Figure 4 Pipeline schematics.

This pipeline was simulated using an industry-grade transient flow model that uses the Method of Characteristics (MOC) to solve the governing equations for fast transients in closed pipes. The MOC is one of the most popular methods for solving unsteady flows due to its accuracy, numerical efficiency, and programming simplicity (Chaudhry, 2013; Ghidaoui et al., 2005; Wylie and Streeter, 1993). Unlike SWMM, this MOC model is not able to represent transition between flow regimes. The results obtained by this MOC model were compared to SWMM modeling results. Both models were set up with a celerity of 500 m s^{-1} and a C_r of 1 was used to estimate the routing time-step. Spatial discretization of $\Delta x = 0.5$ m was adopted in SWMM. The results using the other modified celerities, C_r, and spatial discretizations produced similar results but they were omitted from this work for the sake of brevity. Data were retrieved on specific locations of the pipeline for comparison. Fig. 5 shows the results of flow and head at these locations for the first 60 seconds of simulation.

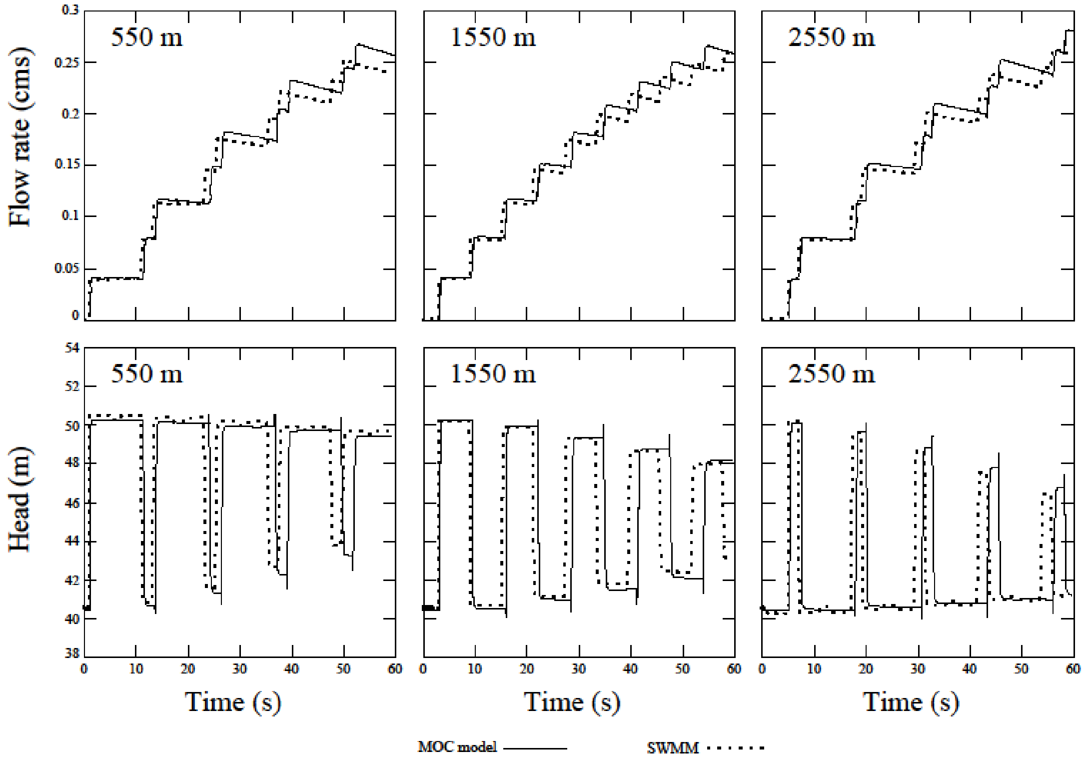

Figure 5 Simulation results for different regions of the pipeline.

Based on the results, it is possible to state that SWMM is capable of representing the flow rate and the head at those locations with satisfactory accuracy when using the modified Preissmann Slot along with spatial discretization. For the first 20 seconds of simulation, when the transient generates the highest head and, consequently, the most critical period, SWMM represents well the transient. However, when simulation time increases, SWMM presents some diffusion that deviates the solution from the MOC model. This situation may be caused by the numerical method implemented in SWMM that uses a method of successive approximations with under relaxation and a convergence tolerance.

4 Conclusions

This work assessed the SWMM capability to simulate certain types of closed pipe transients. It was found that, if SWMM is set up carefully - with additional spatial discretization, a modified version of the Preissmann Slot based on expected celerity, and time-step estimated following the CFL stability condition -, SWMM can represent fast transients and certain flows conditions that the model was not originally conceived for.

The results obtained in this work showed that the original implementation of the Preissmann Slot method in SWMM 5.1.0.13 is not able to represent closed pipe fast transients since the slot adopted is too wide, creating unrealistic transient storage and delaying the propagation of transient pressures. Furthermore, without spatial discretization, none of the cases analyzed in this work yielded results consistent with theory. This confirms the findings of earlier works by Ridgway (2008), Vasconcelos et al. (2018), Pachaly et al. (2019) and Pachaly et al. (2020) in the context of mixed flows (i.e. pressurized and free surface flows). These studies also showed spatial discretization as a factor to improve the SWMM accuracy when representing unsteady flows.

The modified versions of the Preissmann Slot algorithm based on predefined values of celerity along spatial discretization represented well the closed pipe transients. The results showed that finer spatial discretization produced results with smaller numerical diffusion and, as consequence, smaller values of the L2 norm. The relation between spatial discretization and L2 norm is almost exponential: when adopting a finer discretization, the *L2* norm decreases almost exponentially.

In order to represent a more realistic case, a comparison was made between this modified approach implemented within SWMM and a benchmark model. SWMM was able to estimate values of flow and head similar to those obtained by the benchmark model. One limitation found is that as simulation goes on diffusion appears and the results start to differentiate from those generated by the benchmark model. However, the maximum value of head was accurately represented and the flow at the beginning of the simulation was also well estimated by SWMM. It is believed that representing these phenomena with this degree of accuracy in an established model such as SWMM may aid engineers and modelers in the first stages of designing different types of collection systems.

Notation

A = cross-sectional area (m^2)

B = slot width (m)

c = celerity (m s^{-1})

C_r = Courant number (-)

D = tunnel diameter (m)

g = gravity acceleration (m s^{-2})

H = hydraulic head (m)

H_{anl} = analytical head change (m)

H^*_{anl} = analytical head change normalized (-)

H_{sim} = simulated head change (m)

H^*_{sim} = simulated head change normalized (-)

H_o = initial head (m)

h_L = local energy loss per unit length of conduit (-)

Q = flow rate (m^3 s^{-1})

S_f = friction slope (-)

t = time (s)

V = velocity (m s^{-1})

x = distance (m)

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