A methodology for linking 2D overland flow models with the sewer network model SWMM 5.1 based on dynamic link libraries

Jorge Leandro and Ricardo Martins

ABSTRACT

Pluvial flooding in urban areas is characterized by a gradually varying inundation process caused by surcharge of the sewer manholes. Therefore urban flood models need to simulate the interaction between the sewer network and the overland flow in order to accurately predict the flood inundation extents. In this work we present a methodology for linking 2D overland flow models with the storm sewer model SWMM 5. SWMM 5 is a well-known free open-source code originally developed in 1971. The latest major release saw its structure re-written in C++ allowing it to be compiled as a command line executable or through a series of calls made to function inside a dynamic link library (DLL). The methodology developed herein is written inside the same DLL in C++, and is able to simulate the bi-directional interaction between both models during simulation. Validation is done in a real case study with an existing urban flood coupled model. The novelty herein is that the new methodology can be added to SWMM without the need for editing SWMM’s original code. Furthermore, it is directly applicable to other coupled overland flow models aiming to use SWMM 5 as the sewer network model.

Key words | coupled models, dual drainage, overland flow models, P-DWave, sewer network models, SIPSON, SWMM, urban flooding

INTRODUCTION

Extreme rainfall events may cause the underground sewer network to surcharge in urbanized areas. In this case a specific type of flooding characterized by a gradually varying inundation process will occur at the surface. In order to simulate its dynamic behaviour, it is of paramount importance that the interaction between the sewer network and the overland flow is accurately characterized (Nasello & Tucciarelli 2005; Blanksby et al. 2007). In the literature, such models are termed coupled urban flood models or dual drainage models (Djordjevic et al. 1999). To date, there is no open-source sewer network model that includes an interaction module for linking with 2D overland flow models. Herein we present a methodology for linking the open-source Storm Water Management Model (SWMM) based on Dynamic Link Libraries (DLL) in C++. The new methodology can be added to SWMM code without the need for editing the original structure, making it compatible with future releases.

The US Environmental Protection Agency (EPA) developed the open-source SWMM in 1971, and it was therefore one of the first published sewer network models. In 1977 the EXTRAN block was added to SWMM by CDM, Inc. (a consultancy firm). EXTRAN was able to dynamically simulate routing along channels and closed conduits. It became one of the most widely used components (or blocks) of SWMM. In 1988 EPA launched Version 4.0, a public domain personal computer version in Fortran-77 (Huber & Dickinson 1988). Communication between blocks was done through exchange files. In 2004 Version 5.0 was released, in which SWMM Fortran-77 blocks were re-written in a platform-independent engine written in C++. Version 5.1 is the last version to date, released

doi: 10.2166/wst.2016.171
in 2014, and is available to download at the US EPA website.

In order to simulate flooding in a realistic manner, sewer network models need to be coupled with overland flow models. This can be achieved by linking either with a 1D surface network model or with a 2D overland flow model (Leandro et al. 2011). The former is computationally faster but requires the application of geographic information system (GIS) methodology for setting up the surface flood inundation paths (Mark et al. 2004; Maksimovic et al. 2009). The latter is computationally more time consuming, but it is easier to set up. Hsu et al. (2000) linked the 2D UIM model with SWMM 4 by editing the file assignments between blocks; it was not necessary to edit the code, but the model could only transfer discharges from the sewer network to the surface. Cea et al. (2010b) calculated the sewer surcharge with SWMM and used it as input as surface runoff on a 2D model (Cea et al. 2007). Chen et al. (2005) and Seyoum et al. (2012) overcame the lack of bi-directional interaction by modifying the Fortran-77 (SWMM 4.0) and the C++ (SWMM 5.0) code when linking it with the 2D model, respectively. Commercial packages such as PCSWMM and XPSWMM (Phillips et al. 2005) provide a linked version between SWMM and 2D models, although the linkage details are not open-source.

Other coupled models have emerged that link 2D overland flow models with non-open-source sewer network models; these include MOUSE-MIKE21 (Carr & Smith 2006; DHI 2006), SOBEK-DELF FLS (Bolle et al. 2006), SIPSON-UIM, SIPSON-P-DWave (Chen et al. 2015) and the models from (Schmitt et al. 2005; Cea et al. 2010a, 2010b; Fraga et al. 2015) and (Borsche & Klar 2014), among others (Vojinovic & Tutulic 2009; Bazin et al. 2014; Leandro et al. 2016). Regardless of the sewer network model used, the interaction discharge from previous models is based on the water level differences between the sewer network manholes and the aboveground surface, and has been extensively detailed in the above referenced publications. However, the methodology for implementing the linking between the sewer network and the overland flow models does vary across models, mainly because it involved recoding of both models to enable the communication between them. The present paper aims to provide a methodology for linking the open-source SWMM model based on DLL in C++.

Future work on developing coupled models can benefit from a SWMM release version ready for coupling with 2D overland flow models.

The next section starts with a short presentation of the hydraulic models used in this paper, followed by a section on the methodology for linking 2D overland flow models to SWMM 5.1. The following section presents the case study and results, and the final section summarizes and concludes the work.

HYDRAULIC MODELS

SWMM 5.1.001: Storm Water Management Model

SWMM is a 1D dynamic sewer network model based on the gradually varied unsteady flow equations (Saint-Venant equations). The network system is idealized as a set of links which are connected at nodes. Links transmit flow from node to node. The primary dependent variable in the links is the discharge \( Q \). The solution is obtained for the average flow in each link, and it is assumed to be constant over a time step. Nodes are modelled as storage elements in the system. The assumption is that the water surface area of a node is equivalent to the surface area of the node itself plus the surface area contributed by half of each conduit connected to the node (Rossman 2008).

The dynamic wave routine uses the continuity and momentum equation in the links and the continuity equation at the nodes. Thus, while momentum and continuity are conserved in the links, only continuity is conserved at the nodes. The momentum equation is combined with the continuity equation to yield an equation to be solved along each link at each time step:

\[
\frac{dQ}{dt} + gA S f - 2V \frac{dA}{dx} - V^2 \frac{dA}{dx} + gA \frac{dH}{dx} = 0 \quad (1)
\]

The equation is discretized in a finite difference form for which the spatial discretization \( dx \) is equal to the length of the conduit \( L \). Thus, velocity \( V \) and conduit cross-sectional area \( A \) are weighted averages of the conduit end values at time \( t \). \( V \) and \( A \) are related to discharge \( Q \), head \( H \) and surface area at the node \( A_n \) and the node storage \( A_{store} \) through the continuity equation at each node:

\[
\frac{dH}{dt} = \frac{\sum Q}{A_n + A_{store}} \quad (2)
\]

Equations (1) and (2) are solved sequentially to determine the discharge in each link and head using Picard...
iterations to integrate the nodal continuity equation over the time step $\Delta t$ (Rossman 2008). The numerical integration of the two equations is accomplished by the modified Euler method. Similarly to other explicit schemes, the time steps ($\Delta t_{1D}$) are limited by the Courant condition:

$$\Delta t_{1D} = \frac{L}{\sqrt{gD}}$$

Time step is limited by the time required for a wave to propagate the entire length of a conduit with diameter $D$ (Equation (3)). During surcharge, and in order to prevent the corresponding $A_3$ becoming 0, a limit on the full conduit width is set equal to the width when the conduit is 96 percent full, the so-called minimum full conduit width parameter. In case of surcharge, and if no storage is imposed in the node, Equation (2) has no solution, and therefore, to guarantee the mass conservation, a perturbation equation is enforced:

$$\Delta H = -\frac{\sum Q}{\sum \partial Q / \partial H}$$

Equation (4) replaces Equation (2) whenever heads need to be computed in the successive approximation scheme developed for surcharge flow (Rossman 2008).

Huber & Dickinson (1988) state that when Froude number exceeds 1.0 the conduit flow is calculated with Manning’s equation using the upstream cross-sectional area and hydraulic radius. Although this simplification prevents supercritical flow from being accurately modelled, it is highly beneficial for the model stability. In addition, since the governing equations are discretized with half the conduit’s length (Rossman 2008), transcritical flow inside a conduit cannot be simulated, since it requires a much finer discretization of the governing equations to be accurately captured (Djordjević et al. 2004).

SWMM 5.1 consists of a platform-independent computational engine written in C++ (Rossman 2008). The code is split into eight functions in a single DLL. Each function is designed to start and end a specific sub-task in SWMM. As such, it is easier to add other functions to the C program to communicate with SWMM 5.1 without the need to modify or edit the input files or the code as in SWMM 4.0. SWMM 4.0 is made of seven blocks, which communicate from one block to another through the use of file assignments (Huber & Dickinson 1988). SWMM 5.1 is therefore clearly computationally more efficient than its predecessor SWMM 4.0.

SIPSON: Simulation of Interaction between Pipe flow and Surface Overland flow in Networks

SIPSON is a 1D dynamic model for the Simulation of Interaction between Pipe flow and Surface Overland flow in Networks (Djordjević et al. 2005). The model simulates the flow in a network as a system of equations for flow through nodes and links for which relations between flow variables at the nodes and at the ends of the links are built based on the node continuity equation.

Unlike SWMM, the model solves the complete 1D Saint-Venant equations by a variant of the Preissmann implicit finite-difference method. The equations are first linearized, and then the set of $2N-2$ equations is reduced to a system of two equations by eliminating the unknowns at internal cross sections and discretized in small spatial steps ($dx$), where $N$ is the number of computational cross-sections along the pipe. Discharge at the end of each link is expressed as a function of water levels in the correspondent nodes. Continuity equation at the nodes is solved by the Euler modified method. All link equations are substituted into the node equations to form a matrix system, which is solved by the conjugate gradient method. Once the water levels are calculated at all nodes, the Saint-Venant equations, are solved for each link. Due to the linearization of the equations the process is iterative. The choice of $dx$ is calculated based on a desired Courant number and $\Delta t_{1D}$; however, and particularly in the case of a jump, relatively small $\Delta t_{1D}$ are advisable in order to minimize instabilities due to shifts in the jump. As such, there is no limitation on $\Delta t_{1D}$ other than a desired level of accuracy.

Manhole surcharge is simulated with the open-slot concept (Preissmann & Cunge 1961). It assumes an imaginary opening in the closed conduit cross-section by adding a narrow open slot along the top. Unlike SWMM, there is no dramatic change of the surface area at the node ($A_i$), and as such, no changes to the continuity equation are enforced. There is, however, an extra volume considered atop of the pipe, which can nonetheless be minimized by reducing the width of the slot. There is no loss of water volume, since SIPSON applies an interactive procedure which will update the correct water levels inside each time step (Cunge et al. 1980). Supercritical flow is handled by reducing the convective acceleration term. The reduction is done locally and gradually depending on the Froude number. This is done to control instabilities in the model, but still keep the ability to handle supercritical flow (Djordjević et al. 2004).
P-DWave: Parallel Diffusive Wave model

The P-DWave model is an overland flow model used to exemplify the methodology for linking to SWMM 5.1. It is a first order finite volume explicit discretization scheme that neglects the inertial terms in 2D shallow water equations. The governing equations are written as:

\[
\frac{dh}{dt} + \nabla (uh) = R
\]  

\[
g \nabla (h + z) = gS_i
\]

where \( h \) = water depth [m]; \( t \) = time [s]; \( u = [u_x \ u_y]^T \) is the depth-averaged flow velocity vector [m/s]; \( u_x \) = flow velocity in x direction [m/s]; \( u_y \) = flow velocity in y direction [m/s]; \( R \) = source/sink term [e.g. rainfall, inflow, surcharge, drainage, etc.] [m/s]; \( g \) = gravity acceleration [m/s²]; \( z \) = bed elevation [m]; \( S_f = [S_{fx} \ S_{fy}]^T \) is the bed friction vector [-]; \( S_{fx} \) = bed friction slope in x direction [-]; \( S_{fy} \) = bed friction slope in y direction [-]. The bed friction is approximated by Manning’s formula:

\[
\begin{bmatrix}
S_{fx} \\
S_{fy}
\end{bmatrix} = 
\begin{bmatrix}
n^2 |u| u_x \\
n^2 |u| u_y \\
h^{4/3}
\end{bmatrix}
\]

\[ n = \text{Manning’s roughness [m}^{1/3}\text{s}] \]. Velocity is defined by \( u^2 = u_x^2 + u_y^2 \). The modulus of the depth-averaged flow velocity vector is obtained by substituting Equation (7) into the velocity equation and solving for \( u \):

\[
|u| = \frac{h^{2/3} (S_{ux}^2 + S_{uy}^2)^{1/4}}{n}
\]

where according to Equation (6), \( S_{ux} = d(h + z)/dx \) and \( S_{uy} = d(h + z)/dy \) are the water level gradients in the x and y direction, respectively [-]. Stability analysis shows that the time step is limited by:

\[
\Delta t_{2D} < \max \left( \min \left( 2\Delta x^2 n \sqrt{S_{uxy}} \right) \cdot \Delta t_{\text{min}} \right)
\]

where \( \Delta x = 2D \) grid spatial discretization [m], \( S_{uxy} \) is the minimum water level gradient, and \( \Delta t_{\text{min}} \) is an imposed minimum time step to avoid too long a computational time. The detailed derivation can be found in Leandro et al. (2014).

Linking methodology for SWMM 5.1

SWMM 5.1 is split into functions inside a DLL which enables an easier usage and linkage to other models. To run a SWMM 5.1 simulation, a minimum of six functions need to be called sequentially (Figure 1(a)). In order to develop a linking methodology for SWMM without the need to edit the original code, SWMM original structure needs to be kept and additional functions need to be added to provide the interface for communicating with 2D overland flow models.

The linking methodology includes three extra functions that need to be written for exchanging information between the two models. To illustrate the DLL use, the typical modeling stages of a 2D flow model are displayed in Figure 1(b) and inserted among similar stages in SWMM, including the three developed functions (Figure 1(b)). The following three functions are added to SWMM 5.1 code: SWMM-Link, SWMM-to-2D and 2D-to-SWMM. SWMM-Link DLL enables the 1D, crest and elevations of the desired sewer network linking nodes to be extracted from SWMM. The simulation time and SWMM time step are also extracted, and used to initiate the linking time steps between the 2D simulation and SWMM, and stop or advance SWMM by one time step. The function takes Node ID to be linked as input data. The SWMM-to-2D function extracts the node water levels during every SWMM simulation time. The function takes Node ID indices as Inputs to exchange the discharge flow. The 2D-to-SWMM function exchanges the discharge between both models, estimated based on the 1D/2D link discharges subroutine from the 2D overland flow model. The function inputs are the Node ID indices of the linked manholes, and the discharge values to exchange. The values can be either positive or negative, depending on whether water is being transferred from or to the 2D overland flow model.

To test the above methodology, we use the P-DWave 2D overland flow model. The 2D model includes two further subroutines, full details of which can be found in previous publications (Chen et al. 2007), (Chen et al. 2015) and (Seyoum et al. 2012). Both subroutines are now summarized for the sake of completion. The 1D/2D link discharges subroutine calculates the bidirectional discharge between the two models. Discharge is based on the water level at the surface \( h_{2D} \), the hydraulic head at the manhole \( h_{1D} \) and the ground surface elevation \( Z_{2D} \). Drainage is determined by either a weir equation (Equation (10)), if \( h_{1D} < Z_{2D} \), or an orifice equation (Equation (11)), if \( h_{1D} > Z_{2D} \).

\[
Q = c_w \Delta w \sqrt{2gh_{2D}}
\]

\[
Q = c_o \Delta w \sqrt{2gh_{2D}}
\]
where \( Q \) is the interacting discharge \([\text{m}^3/\text{s}]\), \( c_w \) is the weir discharge coefficient, \( w \) is the weir crest width \([\text{m}]\), \( A_{mh} \) is the manhole area \([\text{m}^2] \) and \( c_o \) is the orifice discharge coefficient. Surcharge is determined based on an orifice equation (Equation (12)) if \( h_{2D} < h_{1D} \).

\[
Q = c_w A_{mh} \sqrt{2g(h_{2D} + Z_{2D} - h_{1D})}
\]  

(11)

\[
Q = -c_o A_{mh} \sqrt{2g(h_{1D} - Z_{2D} - h_{2D})}
\]

(12)

The 2D model step subroutine is used to synchronise the two models. This is necessary because the time steps in both models are different. The time step in SWMM \( (\Delta t_{1D}) \) is always larger than in P-DWave \( (\Delta t_{2D}) \). One possibility is to impose a smaller time step in SWMM equal to the P-DWave time step and exchange discharges at every step. However, this solution increases the time spent on communication between both models considerably. Another alternative is to use SWMM run time as synchronisation time \( (T_{sync}) \). In this case, the P-DWave time step is adjusted whenever the 2D model run time is expected to exceed the synchronisation time.

\[
\Delta t_{2D} = \min\left\{ \left( T_{sync} + \Delta t_{1D} - \sum \Delta t_{2D} \right), \Delta t_{2D} \right\}
\]

(13)

Further details of the time synchronisation technique applied can be found in (Chen et al. 2007). Both subroutines need to be coded into the 2D model in order to communicate with SWMM. Since different programming languages are used across 2D models, we focus this section on the linking methodology for SWMM 5.1 code, which remains valid for any 2D model. The methodology is validated with the SIPSON/P-DWave model (Chen et al. 2015) in a real case study described in the next section.
377 × 269 rows with a spatial resolution of 2 × 2 meters. In total, there are 84 manholes connecting the sewer network to the overland sewer system and one free outlet to a tributary of the river Aire downstream of the study area (Figure 2). The methodology is applied to the 2D P-DWave overland flow model (termed SWMM/P-DWave) and the existing SIPSON/P-DWave coupled model. In order to ensure a meaningful test and validation process, both sewer network models will be using the same routing time step (Δt = 2 s). Runoff input hydrographs are calculated with SIPSON runoff module (BEMUS) as a function of each manhole’s sub-catchment area (Maksimović et al. 2009) and applied to both sewer models. A 100-year return period is used with a synthetic block of 1 h and an intensity of 42 mm. The hydrographs are applied as internal boundary conditions in each manhole of the sewer models. Because runoff is determined before the dynamic simulation, it cannot account for the drainage capacity of the manholes. As such, this assumption may be incorrect if manholes surcharge while receiving input from the runoff hydrographs. Ideally, runoff should only be input to each manhole if enough drainage capacity is available. This assumption is nonetheless considered acceptable to ensure a consistent comparison between models. In coupled models, any excess runoff input into the manholes will directly surcharge to the surface. A similar assumption was used in Leandro et al. (2009).

Sensitivity analysis on SWMM minimum full conduit width

This section presents a sensitivity analysis on SWMM minimum full conduit width. Figure 3 shows the comparison of the discharges of all manholes of the sewer system for three different minimum full conduit widths, namely, 0.39 × D, i.e. SWMM default value, 0.12 × D, an optimized value to fit SIPSON discharge values, and 0.05 × D. The last value is selected in order to provide SWMM with an equivalent value to SIPSON Preissmann slot width. Table 1 shows a sensitivity analysis of SWMM minimum full conduit width. The table displays the comparison of the overland surface volume differences between SWMM/P-DWave and SIPSON/P-DWave coupled models, and the sum of the root-mean-square errors (RMSE) from all discharges. The depth for which the minimum full conduit width starts to take effect is found in getWidth SWMM subroutine and is not available in the graphical user interface.

Results

In this section, the testing and validation results are shown only for SWMM minimum full conduit width of 0.12 × D. Figure 4 shows the validation results from the linking methodology for discharges from/into the manholes, water levels...
at the overland surface nodes above the manhole, and piezometric levels inside the manholes. Except for the first (Figure 4(a)), the selection criteria are to show the manholes having the largest differences between the two coupled models (see Figure 3(b)). The validation results for the maximum flood inundation extents including the absolute differences in surface water depths on the 2D surface grid are shown in Figure 5.

In order to propose a novel methodology for linking 2D flood inundation models that can be added to SWMM without the need for editing or modifying the original code, we aim to achieve two goals: that the initial code is not modified and that the results are in good agreement with an existing verified model. The presented results showed that neither could be sustained. SWMM showed smaller sewer surcharges than SIPSON (Figure 3) and consequently less surcharge volume on the surface (Table 1). All 84 manholes tested in SWMM showed smoother results than in SIPSON. Through a sensitivity analysis, the source of this discrepancy was identified to be SWMM minimum full conduit width and not the methodology for linking with SWMM. Therefore, it would be desirable that this parameter does not remain fixed in SWMM and that future releases of the user interface include an option to modify it.

SIPSON applies the Preissmann slot concept for modelling pressurized flows, for which case the wave celerity \(c\) is given by \(c = \sqrt{gA/B}\). In order to replicate the celerity of pressurized flow, the width of the slot \(B\) has to be kept very small. Although SWMM does not apply the Preissmann

<table>
<thead>
<tr>
<th>Depth for minimum full conduit width start (m)</th>
<th>SWMM minimum full conduit width (m)</th>
<th>SWMM volume at the Surface (m³)</th>
<th>Volume difference between SWMM and SIPSON (%)</th>
<th>Sum of root-mean-square errors from all discharges (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.96000 × D</td>
<td>0.39 × D</td>
<td>15992</td>
<td>−13.7</td>
<td>0.89</td>
</tr>
<tr>
<td>0.99668 × D</td>
<td>0.12 × D</td>
<td>17859</td>
<td>−3.7</td>
<td>0.25</td>
</tr>
<tr>
<td>0.99936 × D</td>
<td>0.05 × D</td>
<td>18404</td>
<td>−0.7</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Comparison of the sum of root-mean-square errors from all discharges. Sensitivity analysis on the minimum full conduit width in SWMM: (a) 0.39 × D (default value, 39% of the diameter), (b) 0.12 × D (optimized value, 12% of the diameter) and (c) 0.05 × D (value set to be equal to SIPSON Preissmann slot width, 5% of the diameter).
slot concept, by limiting the minimum full conduit width, SWMM is actually restricting the wave celerity when the flow becomes pressurized (getWidth subroutine in SWMM). A sensitivity analysis on this parameter reveals that for an equivalent slot width of 0.39 × D (default value), when compared with 0.05 × D in SIPSON, the wave propagation in SWMM is characterized by a large lag; hydraulic head in the sewer system is lower and smoother, and discharges are therefore smaller than in the SIPSON coupled model (Figure 3(a)). By reducing the minimum full conduit width to 0.12 × D, the discharges in both models are in almost perfect agreement (Figure 3(b)), and the total difference between volume surcharge in SWMM and SIPSON reduces from −13.7% to −3.7% (Table 1). By setting SWMM minimum full conduit width to be equal to SIPSON Preissmann slot width, the surface volume difference becomes almost negligible; however, some instabilities start to appear in SWMM discharges. These can be recognized in the oscillatory behaviour seen in Figure 3(c). Since explicit schemes (as in SWMM) are subject to the Courant condition (Equation (3)), they require very small Δt in order to avoid instabilities. In this case, by reducing the selected Δt to values lower than 2 s, these instabilities would tend to disappear. In any case, the results with 0.12 × D are already quite good; hence, for the sake of validation of the methodology, we will keep the same Δt of 2 s.

It must be mentioned that the optimum SWMM minimum full conduit width depends on the selected objective function. Indeed, Figure 3 and Table 1 show relevant differences between SWMM and SIPSON. From Table 1, the volume difference with the best agreement between SWMM and SIPSON is obtained with 0.05 × D, while for the sum of RMSE of all discharges, the best agreement is obtained with 0.12 × D. As such, it is clear that SWMM minimum full conduit width can be optimized for different purposes. In addition, the results suggest that SWMM minimum full conduit width can be utilized together with Δt to improve the computational efficiency of SWMM and reduce the model instabilities (as discussed in the previous paragraph).

The agreement between results at the linking manholes provided by the linking methodology for SWMM is excellent (Figure 4). The piezometric level in the manholes, the water level at the surface and the exchanged discharges are very similar, with differences occurring only during pressurized flow in a small number of nodes (Figure 4(c)) and in the transition between pressurized and free surface flow (Figure 4(e)). In the latter, small oscillations can be seen in the piezometric head, which indicates that small discharge exchanges are present near the slot transition. SWMM smaller oscillations are due to the average discretization of Q and H, since only one value is calculated per link, while SIPSON discretizes each link in small distance steps, dx, which makes it more prone to such oscillations. It is noteworthy to emphasize at this point that, despite the simplified SWMM solution along each link, the agreement between both models is excellent. No doubt, the fact that all conduits in this case study have subcritical slopes plays an important role. Except for practical reasons in areas with very steep slopes, subcritical slopes are preferable in sewer networks. In those exceptional cases and in localized spots where supercritical flow may occur, the results between SWMM and SIPSON would necessarily differ. Indeed, one of the drawbacks in SWMM is that it cannot handle supercritical/transcritical flow accurately, as described previously.

The maximum flood inundation extents produced by the linking methodology for SWMM are in very good agreement with the ones obtained with the SIPSON coupled model. The flood inundation extent is very similar (Figure 5(a) and (b)) with some small differences in the water depths (Figure 5(c)). The differences are within the range of ±0.1 m with very few outliers. These small differences can be explained by the differences in the conceptualization of the SWMM and SIPSON models. One is the simulation of surcharge flow already discussed at the beginning of this
section. Another is the reduction of $Q$ and $H$ to a single average value per link in SWMM, which greatly simplifies the solution, and finally, the SIPSON implicit scheme which implies that a linearized version of the Saint-Venant equations is being solved. The fact that flooding is a nonlinear dynamic phenomenon which is being solved by a numerical approximation means that any differences in the models will tend to amplify with time and become more visible with the increase of the flood extent.

Regarding efficiency, SWMM/P-DWave takes approximately half the time taken by SIPSON/P-DWave. For a 6 h flood event in Keighley, SWMM/P-DWave takes about 20 min on an Intel Core i7 2640 CPU (2.8 GHz). One of the reasons is the efficient DLL structure used, which during the simulation phase is accomplished with just two functions. The first function (SWMM Link) is only called once to retrieve the data necessary for linkage between SWMM and the overland flow model. The two following functions (SWMM-to-2D and 2D-to-SWMM) exchange the essential data between the two models without changing SWMM optimized code. Another important reason is the heavier numerical scheme in SIPSON. Indeed, SIPSON can simulate transcritical flow at a cost of solving a more expensive numerical scheme. Firstly, a large matrix system needs to be solved by the conjugate gradient method with discharges expressed as water levels at the corresponding nodes, and secondly, the full Saint-Venant equations for each link need to be solved with a high spatial resolution. In contrast, SWMM has a much lighter numerical scheme and can thus provide similar results in half the computational time required by the SIPSON coupled model for this case study.

A final consideration is in relation to the SIPSON time step. Since SIPSON applies an implicit scheme, it is possible to optimize its computational efficiency. As discussed in the SIPSON section, $\Delta t$ is calculated for each link based on a desired Courant number (set to 4 in the present study) and $\Delta t_{1D}$. As such, it is possible to select a larger $\Delta t_{1D}$ and reduce the required CPU time. Herein a model convergence would have to be studied. A larger $\Delta t_{1D}$ implies that the synchronization time ($T_{sync}$) is also larger. Water is therefore retained at the surface model or at the sewer system longer before being transferred to the other model. Although out of the scope of this paper, it is foreseen that by studying SIPSON’s model convergence and/or by implementing a variable time step, it would be possible to find an optimal compromise between computational efficiency and model accuracy. As discussed earlier, herein the same $\Delta t_{1D}$ is used in both sewer models in order to ensure a meaningful validation of the linking methodology.

**CONCLUSION**

In this paper, a new methodology for linking 2D flood inundation models with the SWMM based on DLL in C++ was presented. The methodology was able to simulate the bi-directional interaction between the sewer and the overland surface flow. The validation was done on a real case study against a verified coupled model. This novel methodology can be added to SWMM without the need for modifying the structure of SWMM’s original code. This will enable seamless linking for SWMM with any other 2D model.

In terms of computational efficiency, the new methodology was shown to double the speed of the computation against the existing coupled model. Nonetheless, the reason for this cannot solely be assigned to the linking DLL structure. Despite the achieved agreement between the two models, the conceptual approaches and numerical schemes are different, which affects the computational efficiency of each model.

For the sake of improving SWMM simulation results, it is suggested that the minimum full conduit width found in the getWidth subroutine in SWMM should be changed. The initial simulation results were smoothed out when compared with the existing coupled model, which used SIPSON as a sewer engine. By changing this parameter, the final results were in excellent agreement. Since the value obtained is likely to be case dependent, the authors suggest that in a future SWMM release, this parameter should be included as editable in the graphical user interface.

**ACKNOWLEDGEMENTS**

We are grateful to Bradford City Council and John Blanksby for access to the sewer network data. Thanks are due to the UK Geomatics Group, Environment Agency, and Ordnance Survey for the provision of LiDAR and digital map data, respectively. The second author thanks and acknowledges the contribution of FCT (Portuguese Foundation for Science and Technology) through the Doctoral Grant SFRH/BD/81869/2011 financed through the POPH/FSE (Programa Operacional Potencial Humano/Fundo Social Europeu) program. This study had the support of FCT through project UID/MAR/04292/2013.

**REFERENCES**


Carr, R. S. & Smith, G. P. 2006 Linking of 2D and Pipe hydraulic models at fine spatial scales. In <i>UDM 2006 Conference, Melbourne, Australia.</i>


Chen, A., Leandro, J. & Djordjevic, S. 2015 Modelling sewer discharge via displacement of manhole covers during flood events using 1D/2D SIPSON/P-DWave dual drainage simulations. <i>Urban Water Journal.</i>


First received 3 September 2015; accepted in revised form 30 March 2016. Available online 11 April 2016.