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Modelling sewer discharge via displacement of manhole covers during flood events using 1D/2D SIPSON/P-DWave dual drainage simulations

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Modelling sewer discharge via displacement of manhole covers during flood events using 1D/2D SIPSON/P-DWave dual drainage simulations

In urban areas, overloaded sewers may result in surcharge that causes surface flooding. The overflow from sewer systems mainly starts at the inlets until the pressure head in the manhole is high enough to lift up its cover, at which stage the surcharged flow may be discharged via the gap between the bottom of the manhole cover and the ground surface. In this paper, we propose a new approach to simulate such a dynamic between the sewer and the surface flow in coupled surface and sewer flow modelling. Two case studies are employed to demonstrate the differences between the new linking model and the traditional model that simplifies the process. The results show that the new approach is capable of describing the physical phenomena when manhole covers restrict the drainage flow from the surface to the sewer network and reduce the surcharge flow and vice versa.

Keywords: coupled 1D/2D modelling, displacement of manhole cover, manhole surcharge, urban flooding

Introduction

Urban drainage systems are fundamental components of flood risk management in modern cities. Like all structural measures, the designed capacities of drainage systems limit their performance such that, when the system capacity is exceeded, flooding may occur during heavy rainfall events. With the rapid advances of computational methods and computer technology, numerical models have become the most popular solution for flood risk analysis. A numerical model can produce enough information to help engineers evaluate flood risk effectively.

Among the numerical models, one-dimensional (1D) sewer hydraulic models are the most commonly used because of the relatively low complexity in the model construction, with high efficiency and short runtime during simulation. Many 1D software packages are currently available for simulation of hydraulics of urban drainage systems. For example, the Storm Water Management Model (SWMM), developed by the US Environmental Protection Agency (Rossman 2010), is generally applied to analyse the hydrodynamics of sewer systems (Campbell and Sullivan 2002; Denault *et al.* 2006). The comprehensive functions and the public availability of SWMM have made it widely adopted as computing engine in commercial software such as MIKE SWMM (DHI Software 2012a), XP-SWMM (XP Solutions 2013) and others.

However, when flooding is considered, most of those models use water stage-volume curves for determining flood depths on the ground surface, whereby excess water that discharges from sewer systems is assumed to be stored above the manhole at which the discharge occurs. This approach is capable of reproducing the flow conditions in the sewer network, but fails to accurately represent the movement of the surcharged flow over the ground surface. Emphasis is now given to the dual drainage concept where the flow interactions between the above ground and the below ground systems are described in the form of major and minor systems (Blanksby *et al.* 2007; Djordjević *et al.* 2005; Maksimović *et al.* 2009; Nasello and Tucciarelli 2005). Natural flow paths and retention basins are regarded as the major drainage system for routing the surface flow, whilst sewer pipes, manholes and inlets are considered as the minor drainage system for conveying the sub-surface flow.

For surface flow modelling, two approaches are commonly used in dual drainage models for different purposes: (1) assuming the surface runoff only flows along drainage channels or streets and flooding occurs at the areas with lower elevations; the surface system is described as a series of links and ponds and the 1D hydraulic models are adopted to simulate the surface flooding (Bolle *et al.* 2006; Leandro *et al.* 2009; Mark *et al.* 2004; Schmitt *et al.* 2005); (2) assuming that the surface runoff will not be restricted by streets and channels; the overland flow is no longer confined to predetermined flow paths and two-dimensional (2D) overland flow models need to be applied. Coupled 2D overland flow and 1D sewer modelling is considered a better tool to predict the movement of surface flows and the interaction between the surface and sub-surface systems. Hsu et al. (2000) adopted SWMM to predict the surcharge hydrographs at each manhole in sewer system and used the discharge calculated by SWMM as inputs to a 2D overland flow model for surface flooding modelling. In this approach, the assumption of uni-directional flow movement from the sewer system to the ground surface failed to describe the phenomena when surface runoff re-enters the drainage system. Hence, the flood extent and depths tended to be over-estimated. Subsequently, Hsu et al. (2002) attempted to describe the return of the flow to the sewer system but did not take into account the interaction of the manhole discharge and its magnitude and the depth of the surface flow.

Chen et al. (2007) considered the surface flow condition when determining the interacting flow between surface and sub-surface systems, and developed the coupled Urban Inundation Model/Simulation of Interaction between Pipe flow and Surface Overland flow in Networks (UIM/SIPSON) model. An adaptive time step was also implemented in the 2D UIM and carefully synchronised with the 1D SIPSON to improve the modelling efficiency. Jahanbazi and Egger (2014) also demonstrated that the coupled HYSTEM-EXTRAN 2D model predicted the urban flooding better than the other conventional dual drainage model. Nowadays, coupled 1D/2D modelling has been widely implemented in commercial software. XP-SWMM (XP Solutions 2013) was developed by adding the TUFLOW 2D module with the XP-SWMM 1D model to enhance the capability for urban flood modelling. The latest version of MIKE Urban (DHI Software 2012b) has seen the integration of MIKE 11, MOUSE and MIKE 21 models to simulate combined river, sewer and floodplain modelling. Similarly, the

InfoWorks ICM has integrated the InfoWorks CS and InfoWorks RS for 1D/2D modelling in both sewers and rivers (Innovyze 2012). However, the model linkages between the above and below ground flow components are usually simplified and in many cases remain unexplained, e.g. Carr and Smith (2006) and Dey and Kamioka (2006), or only consider the discharge through the multiple-inlets (Leandro *et al*. 2007).

In general, the surface and sub-surface systems are modelled separately and linked via the discharge through manholes or inlets. For the drainage condition, the surface runoff is collected by inlets and drained into manholes, and the flow rate from the surface to the subsurface system can be calculated using the rectangular weir equation. Shepherd et al. (2012) measured the discharge collected by road gullies to determine the efficiency of inlet collection. Bazin et al. (2014) studied numerically and experimentally (in laboratory conditions) the exchanges between surface flow and surcharged flow in pipes. Galambos (2012) and Djordjević et al. (2013) compared experimental measurement to the numerical modelling results obtained by a 3D Computational Fluid Dynamics (CFD) model to evaluate the typical UK gully flow during drainage and surcharge conditions. Lopes et al. (2013) and Martins et al. (2014) used OpenFoam to numerically study the discharge and surcharge from a typical Portuguese gully and verified the results in the Multiple-Linking-Element (MLE) experimental facility.

When the piezometric head in a manhole reaches the ground elevation, most linking models assume that the surcharge immediately occurs from the manhole and use the orifice equation to determine the discharge. In reality, the weight of the manhole cover itself may delay the process of surcharging and details of the dynamics of this process have not been discussed much in the literature. This is a phenomenon highly relevant from the practical point of view because a displaced manhole cover may be a serious hazard, as illustrated e.g. in the "sewer explosion" event (YouTube 2007). Despite the extensive literature on drop manholes (Carvalho and Leandro 2011; Granata *et al.* 2014) and manhole junctions (Hager and Gisonni 2005; Saldarriaga *et al.* 2012), there is very little research on manhole cover displacement. Walski et al. (2011) investigated the behaviour of surcharged manholes and the equations to describe the flow discharge. When the manhole cover is lifted by the pressure in the sewer, the flow through the gap between the cover and the casting behaves like orifice flow. When the pressure is high enough to remove the manhole completely, then the flow regime will change to weir flow. They concluded that the pressure head in a manhole may lift the manhole cover allowing the water to overflow via the lifted gap. However, a high enough pressure to remove the manhole cover completely is unlikely to occur such that the transition from orifice flow to weir flow seldom happens.

In this paper, we develop a new linkage model to simulate the flow exchange between the surface and the sewer systems, which includes the discharge from the connected inlets and the lifted manhole cover. The methodology applied in this paper is described in the next section, followed by the applications that include a hypothetical and a real case study. The results will be discussed and the last section will conclude the work.

Methodology

In the study, we coupled the 2D Parallel Diffusive Wave (P-DWave; Leandro *et al.* 2014) and the 1D SIPSON models as a new dual-drainage model for urban flood modelling. The two models are linked via the discharge from manholes and inlets at each time step, considering the flow conditions in the surface and sub-surface systems simultaneously.

P-DWave overland flow model

The P-DWave model neglects the initial terms in 2D Shallow Water Equations (SWE) such that the governing equations are written as:

$$\frac{dh}{dt} + \nabla(\boldsymbol{u}h) = R \tag{1}$$

$$g\nabla(h + z) = g\boldsymbol{S_f} \tag{2}$$

where, h = water depth [m]; t = time [s]; $\boldsymbol{u} = [u_x \quad u_y]^T$ is the depth-averaged flow velocity vector [-]; u_x =flow velocity in x direction [ms^{-1}]; u_y = flow velocity in y direction [ms^{-1}]; R= source/sink term [e.g. rainfall, inflow, surcharge, drainage, etc.] [ms^{-1}]; g = gravity acceleration [ms^{-2}]; z = bed elevation [m]; $\boldsymbol{S_f} = [S_{fx} \quad S_{fy}]^T$is the bed friction vector [-]; S_{fx} = bed friction slope in x direction [-]; S_{fy} = bed friction slope in y direction [-]. The bed friction can be approximated using Manning's formula:

$$\begin{bmatrix} S_{fx} \\ S_{fy} \end{bmatrix} = \begin{bmatrix} \dfrac{n^2|\boldsymbol{u}|u_x}{h^{4/3}} \\ \dfrac{n^2|\boldsymbol{u}|u_y}{h^{4/3}} \end{bmatrix} \tag{3}$$

where, n = Manning's roughness [m$^{-1/3}$s]. The modulus of the depth-averaged flow velocity vector is given by:

$$|\boldsymbol{u}| = \frac{h^{2/3}\left({S_{wx}}^2 + {S_{wy}}^2\right)^{1/4}}{n} \tag{4}$$

where, $S_{wx} = d(h + z)/dx$ is the water level gradient in x direction [-]; $S_{wy} = d(h + z)/dy$ is the water level gradient in y direction [-].

P-DWave adopts the first order finite volume explicit discretization scheme to solve water depth for next time step in Equation (1) on a regular grid. Equation (2) is then applied to determine the velocity between grid cells. Readers are referred to Leandro et al. (2014) for details of the numerical scheme used by P-DWave.

SIPSON sewer model

SIPSON is a 1D sewer network model that simultaneously solves continuity equations for network nodes, energy equations for nodes and pipe/channel ends, the complete Saint Venant equations for flow in conduits and streets, and equations for other link types (pumps, weirs, etc.). The node continuity equation can be written as

$$A_m \frac{d(h_m + z_m)}{dt} = Q_{ex} + \sum_{i=1}^{N} Q_i \tag{5}$$

where, $A_m =$ horizontal cross-sectional area of node [m^2]; $h_m =$ water depth at the node [m]; $z_m =$ bottom elevation of the node [m]; Q_{ex} is the external inflow, when positive, to the node (drainage form ground surface, surface runoff, wastewater etc.) or the surcharged outflow, when negative, from the node [m^{3}s^{-1}]. $i =$ index of node [-]; $N =$ number of links joining a node [-]; $Q_i =$ discharge flowing from the link to the node [m^{3}s^{-1}]. Details of the governing equations and the solution procedures are described in (Djordjević *et al.* 2004). SIPSON can accommodate multiple-inlets in a single manhole by applying the Multiple-Linking-Element (Leandro *et al.* 2007).

1D/2D coupling

We simulate the flow dynamics on overland surface and in sewer networks simultaneously by coupling SIPSON and P-DWave models. The two models are executed individually and linked by exchanging information obtained at proper locations and times for appropriate linkages (Chen *et al.* 2007). In this study, we assume that the grid elements containing manholes are the locations where interactions occur, and the time step used in SIPSON is regarded as the timing for the model linkage.

The bidirectional interacting discharge is calculated according to the water level difference between sewer network and overland surface. The following considers the manhole bottom elevation as the referencing datum: h_{1D} is the pressure head at manhole [m], h_{2D} is the water depth at ground surface [m], and z_{2D} is the ground surface elevation above the datum [m].

Model Linking via Manholes (Model L-M)

The sewer and surface model are coupled via the flow through manholes, where the discharge is calculated using weir or orifice equations.

- Drainage condition

When the water level on the ground surface is higher than the water head at the manhole, the runoff from the surface flowing into the manhole is determined by either the weir equation (Equation (6)), if the pressure head in the manhole is below ground surface elevation, or the orifice equation (Equation (7)), if the pressure head in the manhole is above the ground elevation.

$$Q = c_w P_i h_{2D}\sqrt{2gh_{2D}} \tag{6}$$

$$Q = c_o A_i\sqrt{2\mathrm{g}(h_{2D} + z_{2D} - h_{1D})} \tag{7}$$

where, Q is the interacting discharge, whose positive value means that the flow exchange is from surface to sewer (drainage flow) and negative value means that the flow from sewer towards overland (surcharge flow) [m^{3}s^{-1}]; c_w = weir discharge coefficient [-]; P_i = weir crest width [m]; c_o = orifice discharge coefficient [-]; A_i = net area of inlet gaps [m^2]; z_{2D} = ground surface elevation above the datum [m]; h_{1D} = pressure head at manhole [m].

- Surcharge condition

When the hydraulic head in the manhole is higher than the water level on the ground surface, the flow in the sewer surcharges to the ground surface via the manhole and the discharge is determined by the orifice equation (Equation (8)).

$$Q = -c_o A_m \sqrt{2g(h_{1D} - z_{2D} - h_{2D})} \quad (8)$$

Model Linking via Manhole and Inlet (Model L-MI)

The sewer and surface model are coupled via the flow through inlets or pressurized manholes. The inlet discharge is calculated using weir or orifice equation and the manhole discharge is explained as following.

- Drainage condition

Same as the drainage condition of Model L-M.

- Surcharge condition

For the surcharge condition, the L-MI approach for surcharge condition is improved by adding the influence of the manhole cover displacement in the overall flow surcharge. In this case, the water head at the manhole is more complex and the details are described as following:

(1) Figure 1a shows the condition that the water level in the manhole is below the bottom of the manhole cover, no surcharge is happening.

(2) Figure 1b shows the condition when the water level in the manhole reaches the bottom of the manhole cover, no surcharge is happening but the pressure head within manhole will continue to increase.

(3) Figure 1c shows the case where the pressure head in the manhole reaches the top of the manhole cover. The pressure is not high enough to lift the manhole cover, but surcharge starts from the connected inlets, if any, which results in the

increase of water depth on the ground surface, as shown Figure 1d. The surcharge flow is determined by orifice equation (Equation (9)).

$$Q = -c_o A_i \sqrt{2g(h_{1D} - h_{2D} - z_{2D})} \tag{9}$$

(4) Figure 1e shows the situation when the pressure head in a manhole reaches $(h_{2D} + h_{ce} + z_{2D} - h_c)$; the pressure is about high enough to lift the manhole cover up; h_{ce} = equivalent head of manhole cover [m]; h_c = thickness of manhole cover [m].

(5) Figure 1f shows that enough pressure is built-up to lift the manhole cover up by a vertical displacement $h_V = h_{1D} - h_{ce} - h_{2D} - (z_{2D} - h_c)$. Apart from the surcharge from the connected inlets, the overflow along the manhole edge, from the gap between manhole cover and resting, is also occurring. The total surcharge discharge can be determined by Equation (10):

$$Q = -c_o (A_i + A_g) \sqrt{2g(h_{1D} - h_{2D} - z_{2D})} \tag{10}$$

For a manhole cover (without surface carving or keyholes), h_{ce} can be expressed as a function of the cover thickness (Equation (11)) or the cover weight and area (Equation (12)).

$$h_{ce} = \frac{\rho_c}{\rho_w} h_c \tag{11}$$

$$h_{ce} = \frac{W_c}{\rho_w \mathrm{g} A_c} \tag{12}$$

where, ρ_c = density of manhole cover material [kg/m^{-3}]; ρ_w = density of water [kg/m^{-3}]; W_c = weight of manhole cover [N]; A_c = area of the manhole cover [m^2]. Equation (11) is only applicable for a simple manhole cover plate so the equivalent head is in proportion of the manhole cover thickness and the density ratio of cover material to water. Often the manhole covers are designed with surface carving or with structural support under the cover, which will change the weight of manhole cover significantly and invalidate the assumption of Equation (11). Hence, Equation (12) is more generally applicable since it considers the manhole weight is uniformly distributed over the cover area regardless of the thickness, while both weight and area information are available in the product description.

In theory, the velocity of the surcharge from manhole edge can be determined by the orifice equation, assuming the cross-sectional area of flow is the gap between the manhole cover and its frame. The discharge is the velocity multiplied by the cross-sectional area of the gap. Walski et al. (2011) found that the orifice discharge from the gap is very small, and therefore we regard this surcharge as a portion of the flow from inlets and neglect the computation of this orifice flow.

(6) Figure 1g shows that the pressure head is high enough to lift the manhole cover up by a vertical displacement larger than the thickness of the manhole cover. In other words, the gap between the ground elevation and the bottom of the manhole cover (i.e., $h_V - h_c$) will allow more surcharge from the manhole directly and potentially cause horizontal movement of the cover if there is a strong surface flow (which is discussed later), or vertical ejection in case of strong pressure oscillations due to transient flow in pipes.

The total surcharge discharge can be determined by Equation (13), where $B_c(h_V - h_c)$ is the cross section area of flow from manhole:

$$Q = -c_o[A_i + B_c(h_V - h_c)]\sqrt{2g(h_{1D} - h_{2D} - z_{2D})} \tag{13}$$

where, $B_c =$ perimeter of manhole cover edge [m].

Case studies

We implemented the two linkage modelling approaches in two case studies to determine the interacting flow between the surface and the sewer systems:

- Model L-M: ignores the existence of inlets and considers that the manhole cover has been removed; it allows the manhole to collect surface runoff and to surcharge freely.
- Model L-MI: considers the inlet and the manhole cover in the linking model, and calculates the discharge based on the methodology described in the previous section. Each manhole is connected to an inlet that collects the surface runoff and surcharges freely until the pressure head lifts the manhole cover up.

Although multiple-inlets can be considered within SIPSON, for the sake of simplicity only single inlets will be applied in this study.

Hypothetical case study

The hypothetical study allows us to analyse the subtle differences between the models L-MI and L-M in a relatively confined and isolated drainage system with few linked manholes. Figure 2a shows the 1500 x 1000 m^2 surface area consisting of three inclined planes each 500m long and with surface slopes 0.002, -0.002 and 0.002 in x-direction, respectively, and 0.001 in y-direction. The surface domain was a closed boundary and the outlet of the sewer network was the only exit of the flow. A drainage network with 11 nodes and 10 pipes was designed to cope with the runoff produced by rainfall up to 10mm/h intensity. The diameters of pipes varied from 0.75 to 1.95m. We applied a 6 hour rainfall event with rainfall intensity starting from 0 to 20mm/h in the first hour, kept constant for four hours, and decreasing to zero in the sixth hour. We simulated 12 hours with the hydraulic modelling to allow surface inundation to recede. The rainfall-runoff hydrographs were calculated by the runoff module in SIPSON (Khu *et al.* 2006) and introduced as inflows at manholes.

Figure 2b and 2c show the maximum flood depths and extents obtained by Models L-M and L-MI, respectively. Figure 2d shows the differences in flood depths between both models. The simulated flood depths in L-MI in the area near the downstream outlet were about 0.05-0.10 m higher than the ones in L-M. Figure 3 shows the discharge hydrograph for each manhole, where positive represents surcharge (outflow) and negative represents discharge (drainage). Figure 4 shows the surcharge from the inlet or the manhole cover of each manhole in L-MI.

Real world case study

The real world case study allows us to analyse the differences between the Models L-MI and L-M in a real drainage system, where the interplay between multiple surcharged manholes is unrestrained and can potentially lead to the amplification of differences between the results due to the two linking models. The study area selected is Keighley (Bradford, UK), as detailed in Figure 5a, bounded by the River Aire and its tributary in the north and the east, respectively, Aire Valley Road (A650) in the south and Bradford Road (B6265) in the west. The digital elevation model (DEM) with buildings was obtained from the Light Detection and Ranging (LiDAR) data at 1m horizontal grid resolution, and 2m x 2m grids were subsequently used for the overland flow simulations. Figure 5b indicates that the ground surface elevation varies from 95m in the southwest to 83m in the northeast. The top elevation of levees along the River Aire was raised to 10 cm above 100 year flood level after a fluvial flooding event in 2000. The sewer network, containing 91 nodes and 91 pipes, carries the flow towards the waste water treatment plant in the south-east, where a flap valve exists to prevent reverse flow from the river channel. The diameters of pipes varied from 0.1 m for upstream gullies to 1.5m for downstream main trunks. The labels represent the index of selected manholes that will be further discussed in the later section. Details of manholes inside the orange dash-lined area are zoomed-in and shown in the box at the top-left corner.

Two main sewer trunks collect runoff from the north-west and the south-west upstream catchments and merge in the area. The discharges from these two main trunks were added to the sewer network as upstream inflow boundary condition. Apart from the two upstream inflow nodes (the upstream nodes of nodes 25 and 62) and the three downstream nodes (the node at the bottom-right and its downstream) that are outside the 2D modelling domain, 85 nodes are coupled with the 2D grid cells to allow flow exchange between surface and subsurface systems. A pluvial event of 20 year return period rainfall of 60 minutes duration with a constant intensity 26 mm/h, was applied to the catchment to analyse the performance of the 1D/2D model. Since we are dealing with a densely urbanized area and a short-duration high-intensity pluvial event, interflow and groundwater flow can be neglected deeming the effective rainfall equal to the total rainfall. Dry weather flow is also neglected given its reduced significance when compared with runoff from a 20 year return period rainfall event.

Figures 5c and 5d show the modelled maximum flood depth and extent obtained by L-M and L-MI. Overall the modelled flood extents and depths are similar. Figure 5e shows the difference of flood depths between both results.

Figure 6 shows the discharge hydrographs for the manholes labelled in Figure 5a, where positive represents surcharge and negative for discharge. Figure 7 shows the surcharge from the inlet or the manhole cover of the labelled manhole in Model MI.

Discussions

Hypothetical case study

For the hypothetical case, the flood extent and depths are almost the same for Models L-M and L-MI in the upstream depression. L-M had higher surcharge flow for nodes 1, 2, 4, 8, 9 and 10 because the weight of the manhole cover is not considered. Thus the surcharge can overflow directly from the manhole, which has a larger area and perimeter than the inlet connected to the manhole. Nevertheless, the built-up pressure of manholes in L-MI manages to increase the flow rate to a close range of the ones in L-M. So the differences of flow rate between the two models are not as large as perhaps expected.

The surface runoff returns to the sewer via nodes 6, 7, 8 and 9. There is no or very little surcharge from nodes 6 and 7. For nodes 8 and 9, which are located in the upstream depression area, the runoff drained back to the sewer during the second half of simulation. The manhole covers prevent the surface runoff returning to the sewer system. Since the water above the crest elevation of the upstream depression can overflow to downstream, the maximum flood depth in the depression is limited in both models. Therefore, L-MI produces higher flood depths only in the area near the downstream outlet.

Real world case study

For the real world case, the result of Model L-MI is quite different from Model L-M. Model L-MI has higher maximum flood depths near the surcharged manholes close to the entrance of upstream trunks. Consequently, the depths in the downstream areas of those pipes are lower than the ones from Model L-M because of the reduced surcharge. The main differences can be seen in several areas. The orange-coloured areas near nodes 49 and 70, L-MI flood depths are about more than 0.1m, and 0.01-0.05 m higher, respectively, than L-M which are due to the slightly higher surcharge at nodes 49 and 70. Although L-M has higher surcharge at node 47, most of the runoff propagates west towards nodes 22 and 46, only limited volume accumulated in the south area next to node 47, where has less drainage in L-MI later. Hence, L-MI flood depth is 0.01-0.05 m higher.

For the green-coloured area near nodes 22, L-MI produces 0.01-0.05 m smaller flood depths because of the slightly lower surcharge rate at nodes 22, 25, 39, 44, 46 and 47. Although node 36 has a lower drainage rate in L-M, the order of magnitude is less than the reduced surcharged from other nodes, it did not result in the increase of flood depth and extent in L-MI.

In L-M, 54 manholes are surcharged during the simulation, while in L-MI 55 manholes are surcharged because the rainfall intensity is higher than the designed capacity. Most of the surcharged flow ponds are in the low-elevation downstream area near the River Aire and cause serious flooding. The inflow from the upstream catchment also results in surcharge conditions in the western part of the modelling domain and the surface water is ponded in a local depression.

Out of the 55 surcharged manholes in L-MI, only 44 have a pressure high enough to lift up the manhole covers, and most of them are along the two main trunks carrying the flow from the upstream catchments into the domain. The higher discharges allow the pressure along the main trunks to build up. The pressure in other surcharged manholes is only sufficient to push the flow out of the sewer system to the ground surface, but not enough to lift the manhole cover up. For nodes 33, 36 and 70, L-MI has a higher surcharge flow rate than L-M because the built-up pressure in the manhole increases the flow rate surcharged from inlets.

Finally it should be added that aside from local reports about recurrent flooding in this particular area, we do not have discharge data from manholes and inlets to validate the results. Indeed this is often the case because real field observation of inlets' discharge is not practiced by the water utilities and overall field observations of intense short-duration rainfall is hazardous to obtain (Leandro *et al.* 2011).

Future work

Figure 8a shows the situation that the lifted manhole cover may be pushed aside if the surface flow is strong enough. The area is decreased due to the horizontal displacement, which in turn reduces the total lift force acting on the manhole cover up till the point that the bottom of manhole cover reaches the ground surface (Figure 8b). This condition is not considered in this paper because of the complexity of the hydrodynamic phenomena involved which requires further research. Future work will sought to replicate manhole cover displacement in controlled laboratory experiments to calibrate the discharge coefficients c_w and c_o. We will also consider how to take into account any effects of air trapped in a manhole within our methodology.

Conclusions

We proposed a new approach to link the sewer network and overland flow for dual-drainage models and tested it in the 1D/2D SIPSON/P-DWave coupled model. The flow interactions via inlet and manhole cover are considered in the proposed Model L-MI, and compared to the previous approach (Model L-M) that only adopted manholes to link sub-surface and surface systems. In L-MI the surcharge is forced to overflow via the inlets which have a smaller cross-sectional area that constrained the discharge, while in L-M the surcharge can freely overflow via the manhole without being obstructed by the cover weight. Therefore, and although the built-up pressure head of the manhole in L-MI increases the discharge rate momentarily, the surcharge flows in L-MI are still slightly lower than the ones in L-M. L-MI predicted lower surface flood depths than L-M. For the latter, the surface flow entered the sewer system via manholes directly which is rather unrealistic because in reality the runoff is mostly drained through the inlets. Thus we believe that the new numerical approach L-MI is better able to describe the phenomena than the more standard L-M method.

Implementation of the proposed model in other 1D/2D models (including commercial packages) would be relatively straightforward. The importance of the proposed approach is not only in terms of more accurate simulation of urban flooding, but also with regard to the potential to minimize the impacts on pedestrians and on traffic – e.g. by analysing critical manholes that are more likely to be left without a cover and when health impacts of flooding are assessed via modelling of concentrations of raw sewage on streets.

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References

Bazin, P., Nakagawa, H., Kawaike, K., Paquier, A., and Mignot, E., 2014. Modeling Flow Exchanges between a Street and an Underground Drainage Pipe during Urban Floods. *Journal of Hydraulic Engineering*, 04014051.

Blanksby, J., Saul, A., Ashley, R., Djordjević, S., Chen, A., Leandro, J., Savić, D., Boonya-aroonnet, S., Maksimović, Č., and Prodanović, D., 2007. Integrated Urban Drainage: Setting the context for Integrated Urban Drainage Modelling in the United Kingdom. Presented at the Aquaterra World Forum on Delta and Coastal Development, Amsterdam, The Netherlands.

Bolle, A., Demuynck, A., Willems, P., Bouteligier, R., Bosch, M.S., Verwey, A., and Berlamont, J., 2006. Hydraulic modelling of the two-directional interaction between sewer and river systems. Presented at the 7UDM&4WSUD Intl. Conf.

Campbell, C.W. and Sullivan, S.M., 2002. Simulating time-varying cave flow and water levels using the Storm Water Management Model. *Engineering Geology*, 65 (2-3), 133–139.

Carr, R.S. and Smith, G.P., 2006. Linking of 2D and Pipe hydraulic models at fine spatial scales. Presented at the 7UDM&4WSUD Intl. Conf.

Carvalho, R. and Leandro, J., 2011. Hydraulic Characteristics of a Drop Square Manhole with a Downstream Control Gate. *Journal of Irrigation and Drainage Engineering*, 138 (6), 569–576.

Chen, A.S., Djordjević, S., Leandro, J., and Savic, D., 2007. The urban inundation model with bidirectional flow interaction between 2D overland surface and 1D sewer networks. Presented at the NOVATECH 2007, Lyon, France, 465–472.

Denault, C., Millar, R.G., and Lence, B.J., 2006. Assessment of possible impacts of climate change in an urban catchment. *Journal of the American Water Resources Association*, 42 (3), 685–697.

Dey, A.K. and Kamioka, S., 2006. An integrated modeling approach to predict flooding on urban basin. Presented at the 7UDM&4WSUD Intl. Conf.

DHI Software, 2012a. *MIKE Urban Collection System*. Hørsholm.

DHI Software, 2012b. *MOUSE Pipe Flow, Reference Manual*. Hørsholm.

Djordjević, S., Prodanović, D., Maksimović, C., Ivetić, M., and Savić, D., 2005. SIPSON - Simulation of interaction between pipe flow and surface overland flow in networks. *Wat. Sci. & Tech.*, 52 (5), 275–283.

Djordjević, S., Prodanović, D., and Walters, G.A., 2004. Simulation of transcritical flow in pipe/channel networks. *Journal of Hydraulic Engineering*, 130 (12), 1167–1178.

Djordjević, S., Saul, A.J., Tabor, G.R., Blanksby, J., Galambos, I., Sabtu, N., and Sailor, G., 2013. Experimental and numerical investigation of interactions between above and below ground drainage systems. *Water Science and Technology*, 67 (3), 535–542.

Galambos, I., 2012. Improved Understanding of Performance of Local Controls Linking the above and below Ground Components of Urban Flood Flows. *PhD Thesis*. PhD thesis, University of Exeter, UK.

Granata, F., de Marinis, G., and Gargano, R., 2014. Flow-improving elements in circular drop manholes. *Journal of Hydraulic Research*, 52 (3), 1–9.

Hager, W.H. and Gisonni, C., 2005. Supercritical flow in sewer manholes. *Journal of Hydraulic Research*, 43 (6), 660–667.

Hsu, M.H., Chen, S.H., and Chang, T.J., 2000. Inundation simulation for urban drainage basin with storm sewer system. *Journal of Hydrology*, 234 (1-2), 21–37.

Hsu, M.H., Chen, S.H., and Chang, T.J., 2002. Dynamic inundation simulation of storm water interaction between sewer system and overland flows. *Journal of the Chinese Institute of Engineers*, 25 (2), 171–177.

Innovyze, 2012. InfoWorks ICM Help v3.0.

Jahanbazi, M. and Egger, U., 2014. Application and comparison of two different dual drainage models to assess urban flooding. *Urban Water Journal*, 1–12.

Khu, S.-T., di Pierro, F., Savić, D., Djordjević, S., and Walters, G.A., 2006. Incorporating spatial and temporal information for urban drainage model calibration: An approach using preference ordering genetic algorithm. *Advances in Water Resources*, 29 (8), 1168–1181.

Leandro, J., Chen, A.S., Djordjević, S., and Savic, D.A., 2009. Comparison of 1D/1D and 1D/2D Coupled (Sewer/Surface) Hydraulic Models for Urban Flood Simulation. *Journal of Hydraulic Engineering*, 135 (6), 495–504.

Leandro, J., Chen, A.S., and Schumann, A., 2014. A 2D parallel diffusive wave model for floodplain inundation with variable time step (P-DWave). *Journal of Hydrology*, 517, 250–259.

Leandro, J., Djordjevic, S., Chen, A., and Savic, D., 2007. The use of multiple-linking-element for connecting sewer and surface drainage networks. *In*: *The 32th Congress of IAHR 'Harmonizing the Demands of Art and Nature in Hydraulics'.*

Leandro, J., Djordjević, S., Chen, A.S., Savic, D.A., and Stanic, M., 2011. Calibration of a 1D/1D urban flood model using 1D/2D model results in the absence of field data. *Water Science and Technology*, 64 (5), 1016–1024.

Lopes, P., Leandro, J., Páscoa, P., and Martins, R., 2013. Numerical and Experimental investigation of a gully under surcharge conditions. *Urban Water Journal*, 1–9.

Maksimović, C., Prodanović, D., Boonya-Aroonnet, S., Leitao, J.P., Djordjević, S., and Allitt, R., 2009. Overland flow and pathway analysis for modelling of urban pluvial flooding. *Journal of Hydraulic Research*, 47 (4), 512–523.

Mark, O., Weesakul, S., Apirumanekul, C., Aroonnet, S.B., and Djordjević, S., 2004. Potential and limitations of 1D modelling of urban flooding. *Journal of Hydrology*, 299 (3-4), 284–299.

Martins, R., Leandro, J., and Carvalho, R.F., 2014. Characterization of the hydraulic performance of a gully under drainage conditions. Water Sci Technol. doi:10.2166/wst.2014.168. *Water Science & Technology*, in press.

Nasello, C. and Tucciarelli, T., 2005. Dual Multilevel Urban Drainage Model. *Journal of Hydraulic Engineering*, 131 (0), 748–754.

Rossman, L.A., 2010. *Storm water management model: User's manual Version 5.0*.

Saldarriaga, J., Bermúdez, N., and Rubio, D.P., 2012. Hydraulic behaviour of junction manholes under supercritical flow conditions. *Journal of Hydraulic Research*, 50 (6), 631–636.

Schmitt, T.G., Thomas, M., and Ettrich, N., 2005. Assessment of urban flooding by dual drainage simulation model RisUrSim. *Wat. Sci. & Tech.*, 52 (5), 257–264.

Shepherd, W., Blanksby, J., Doncaster, S., and Poole, T., 2012. Assessment of Road Gullies. *In*: *Proceedings of the 10th International Conference on Hydroinformatics, HIC 2012*. Presented at the 10th International Conference on Hydroinformatics, Hamburg, Germany.

Walski, T.M., Whitman, B., Kelly, B., Leaman, M., and Loughran, D., 2011. Predicting head loss vs. flow relationship for overflowing manholes. *In*: *Urban Water Management: Challenges and Opportunities*. Presented at the Computing and Control for the Water Industry 2011, Exeter, UK: Centre for Water Systems, University of Exeter, 277–282.

XP Solutions, 2013. XP-SWMM Stormwater and wastewater management model: Getting started manual.

YouTube, 2007. Sewer explosion [online]. Available from: https://www.youtube.com/watch?v=BRpGkY1P94c [Accessed 13 May 2014].

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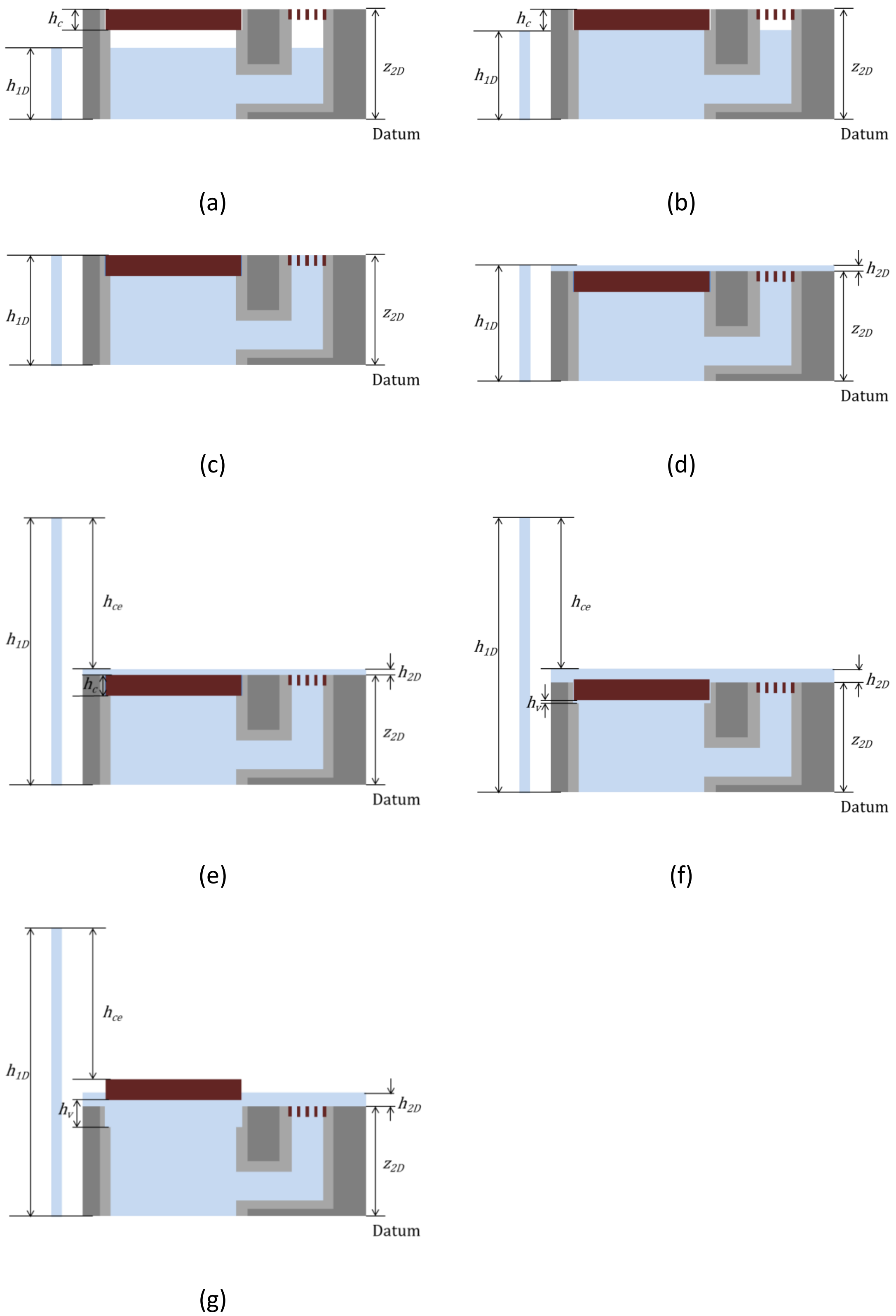

Figure 1 The transition progress for the sewer flow to surcharge from inlet and manhole to water level with manhole below the ground surface and to lift the manhole cover

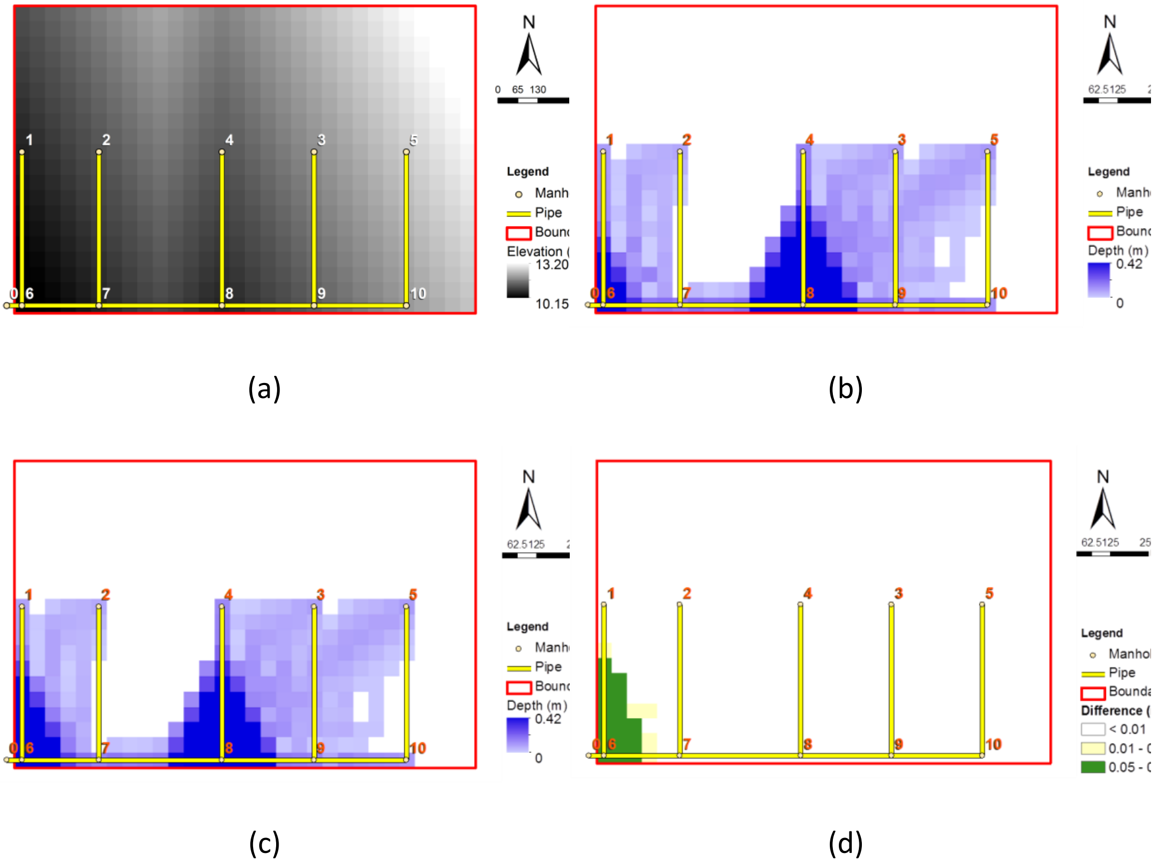

Figure 2 (a) The terrain and the sewer network , (b) the maximum flood depth simulated by Model L-M and (c) Model L-MI, and (d) the difference in simulated maximum flood depth between Model L-M and L-MI (Model L-MI minus Model L-M) for the hypothetical case study

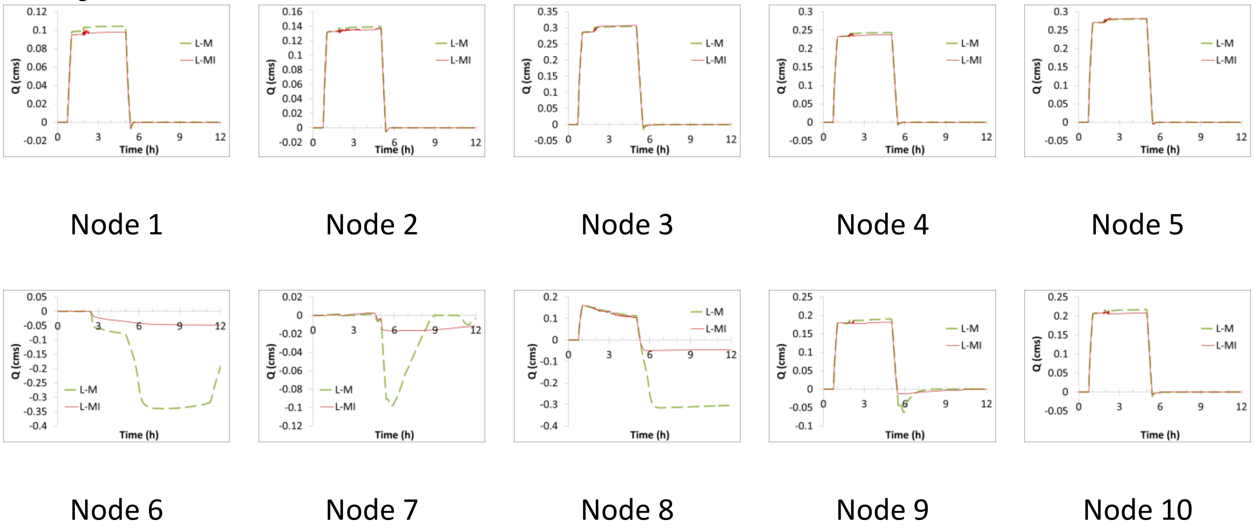

Figure 3 The surcharge (positive) and drainage (negative) hydrograph of nodes from L-M and L-MI of the hypothetical case study

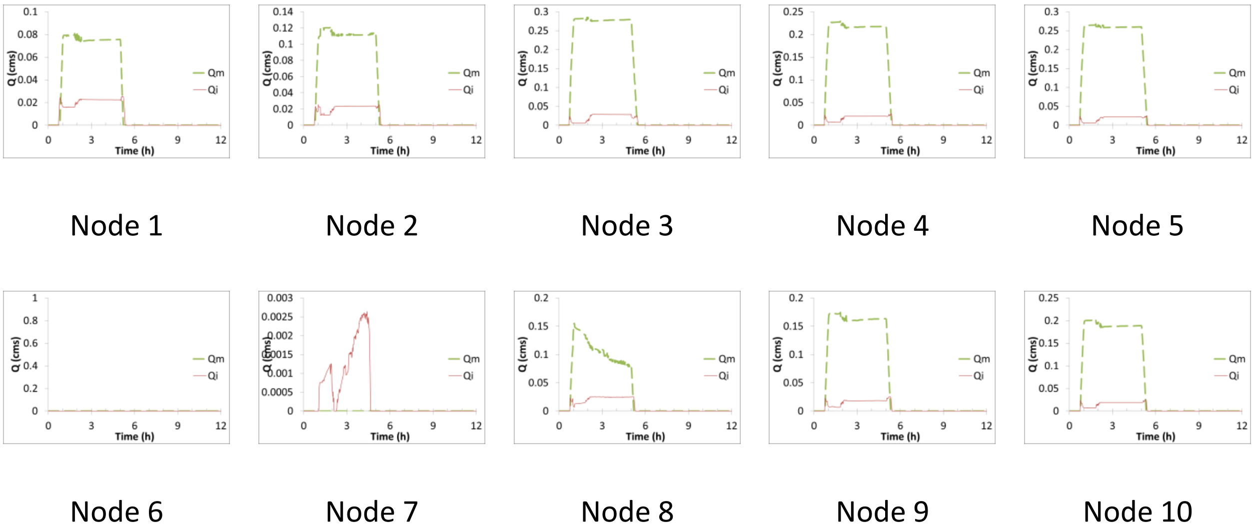

Figure 4 The surcharge from inlet (Qi) or from lifted manhole cover (Qm) in Model L-MI of the hypothetical case study

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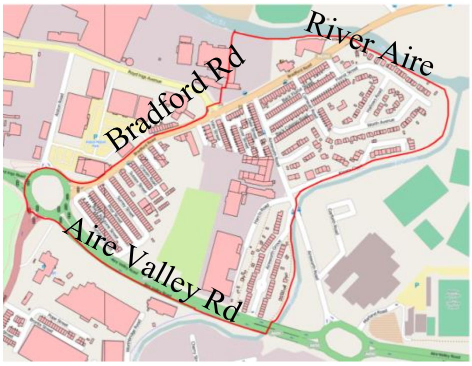

(a)

(b)

(c)

(d)

(e)

Figure 5 (a) The street map and the boundary, (b) the sewer network system and the terrain elevation, (c) the modelled maximum flood depth of 20-year event using Model L-M and (d) Model L-MI, and (e) the difference of modelled maximum flood depth between two modelling approaches (Model L-MI minus Model L-M) for the real world case study

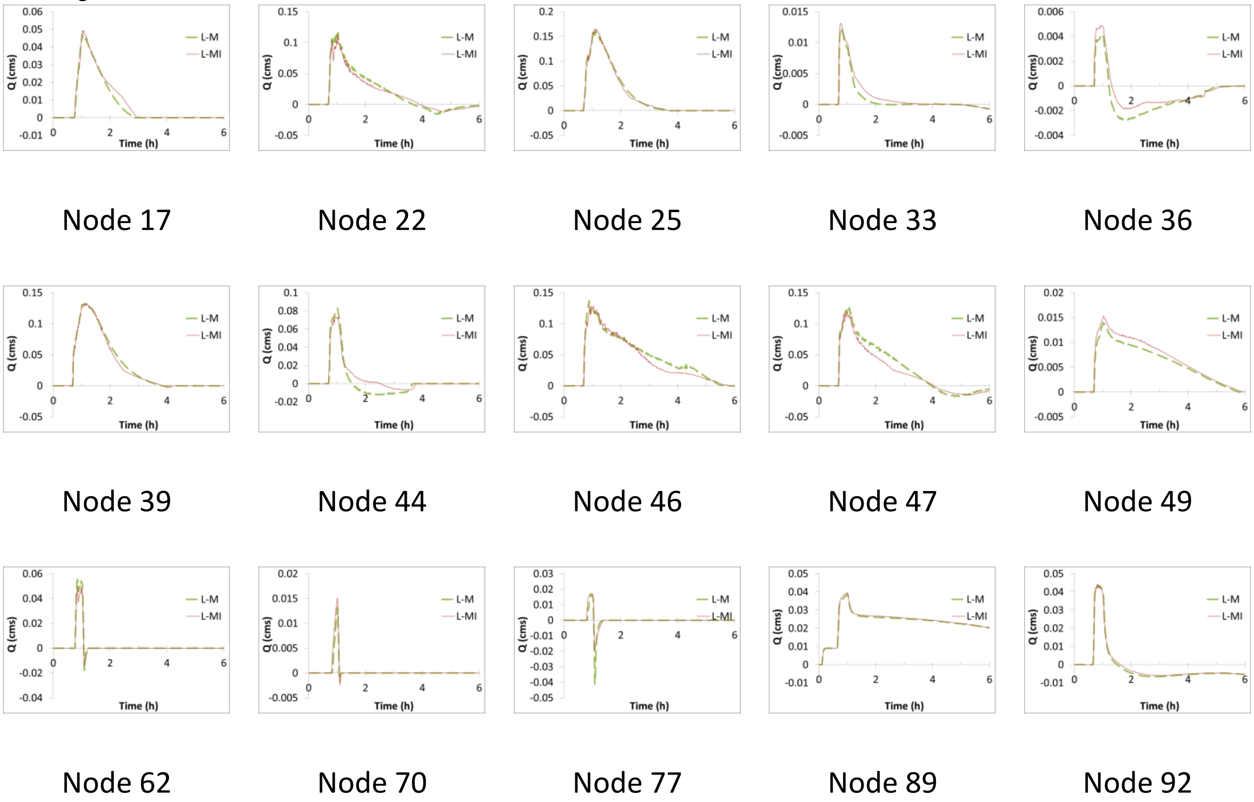

Figure 6 The surcharge (positive) and drainage (negative) hydrograph of nodes from Model L-M and L-MI for the real world case study

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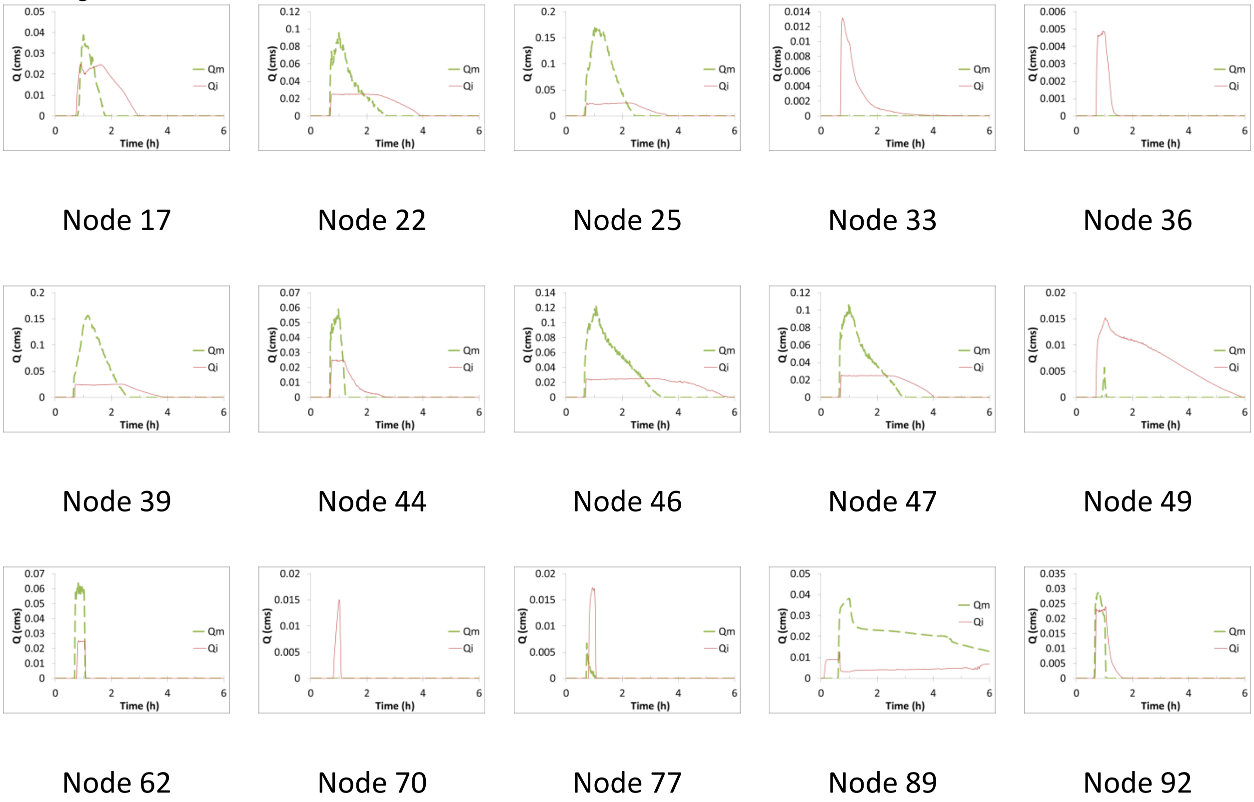

Figure 7 The surcharge from inlet (Qi) or from lifted manhole cover (Qm) in Model L-MI for the real world case study

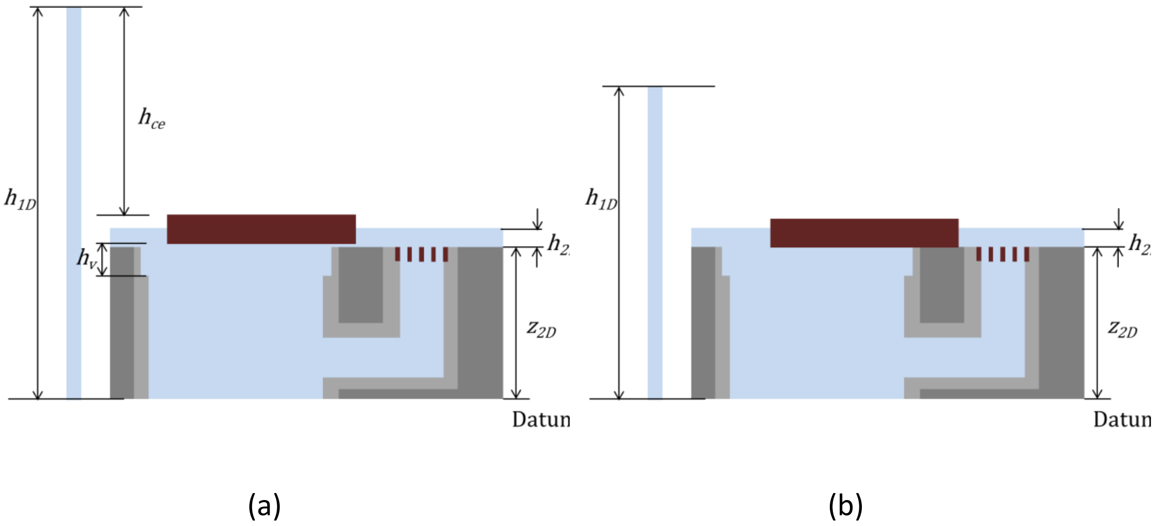

Figure 8 Manhole cover being pushed aside, vertical displacement h_V decreases due to reduced lifting force