A Two-dimensional pollutant transport model for sewer overflow impact simulation

Assela Pathirana[1], M. Dikman Maheng[1,2], Damir Brdjanovic[1]

[1]*UNESCO-IHE, Institute for Water Education, Westvest 7, Delft, The Netherlands*

[2]*Muhammadiyah University of Kendari, Dept. of Environmental Engineering, Faculty of Engineering, Kendari, Southeast Sulawesi, Indonesia*

Abstract

The increasing number of people living in urban areas has influenced performance of the urban water system. Inadequacy of drainage systems generate urban floods resulting in material loss, public health hazard and environmental deterioration. The harmful pollutant concentrations often found in surface water during urban flood events raise many public safety and environmental issues. Many widely available 1D/2D coupled models do not provide a facility to simulate two-dimensional pollutant transport. In this research, we developed a 1D/2D coupled pollutant transport model for sewer over-flow impact simulation. The 2D pollutant model implements the advection-dispersion process for inter-cell scalar exchange, while assuming the irregular triangular model cells to be well-mixed. The model is suitable for simulating dissolved pollutants that are not subjected to significant (bio)chemical transformations. The model is validated by implementing several analytically solvable problems and demonstrated in two case studies from Garforth in United Kingdom and Can Tho in Vietnam. The model integrates the inundation and pollutant transport processes in a convenient 1D/2D coupled package.

Keywords : *Inundation, Urban, Drainage, Flood, Scalar transport, coupled model*

Introduction

The Urban growth has globally escalated to a phenomenal level. As one important consequence, many cities experience urban floods that bring about considerable damage to the human life and urban environment. More than half of the world population already live in cities (UN-HABITAT, 2010). The projection shows that the annual growth for urban population at the global scale is expected about 1.9% from 2010 to 2015. Taken together with the inevitable background trend of climate change and increasing sever asset performance degradation, urban growth could cause the flood risk to dramatically increase (Semadeni-Davies et al., 2008).. In this context, availability of accessible modelling tools to simulate the damage caused by sewer overflow flooding, is critical to objectively evaluate the risks and propose effective remedial measures.

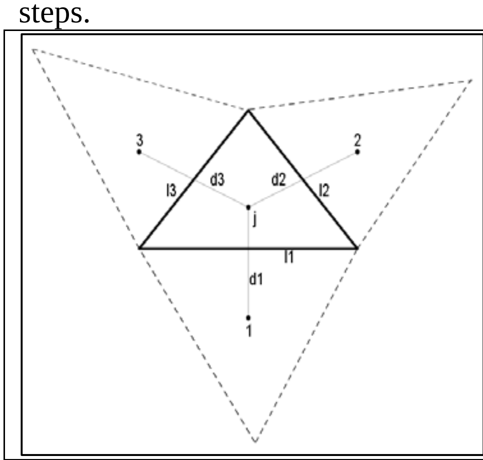
Most of the sewer systems in large cities are of combined type. (Butler and Davies, 2004) where wastewater and surface runoff are transported in the same pipe during rain events. This type of system is usually equipped with Combined Sewer Overflows (CSOs) used to directly discharge the water into water course. In the case of combined-sewers the surcharge events can be particularly harmful to the urban public health and environment, due to the fact that the flood water contain harmful pathogens and pollutants pollutants such as suspended solids, nutrient (phosphorus and nitrogen), organic carbon, metals, Sulphur, Pesticides, etc. (Diaz-Fierros et al., 2002; Hood et al., 2007; Passerat et al., 2010). While in the case of separate sewer systems this hazard is relatively minor, unexpected events like cross-contamination of drains from sewers may make the pollutant consideration a valid issue.

Recent years have seen a number of studies using simulation models to simulate the process of pollutant transport and distribution (Benkhaldoun et al., 2007; Hood et al., 2007; Semadeni-Davies et al., 2008; Zoppou, 2001). Some computer models work in 1D2D integrated system while some of them can be used in either 1D or 2D system. Delelegn et al. (2011) integrated 1D drainage model SWMM5 (Rossman, 2010) with 2D flood Brezo (Begnudelli and Sanders, 2006) to implement a bi-directionally coupled 1D2D model which can be used to simulate inundation events and to predict flood damages due to drainage-surcharge in urban areas. This integrated model did not have a facility to simulate pollutant transport due to sewer overflow in urban areas. In this paper we present the development and application of 1D2D coupled pollutant transport scheme to enhance the SWMM-Brezo model.

Hydrodynamic and Pollutant Transport Model

Storm Water Management Model (SWMM) is a 1D hydrodynamic model which can be used to simulate runoff quantity and quality, particularly in urban areas. SWMM is a physically based, discrete-time simulation model which employs conservation laws of mass, energy and momentum (Rossman, 2010). SWMM has ability to simulate pressurized flow, backwater and surcharged through its dynamic wave routing facility. Pollutant simulation in SWMM is done by assuming that each segment in sewer system acts as a simple Continuously Stirred Tank Reactor (CSTR) (Ramaswami et al., 2005).

Brezo is a hydrodynamic model based on 2D shallow water equations combining a fluid continuity equation and two momentum equations. Both fluid continuity and momentum equations are solved using finite volume method involving direct discretization of computational domain in integral form (Begnudelli and Sanders, 2006). In order to implement pollutant transport process in Brezo, we implemented advection-dispertion exchange at model cell boundaries, assuming the model cell to be fully mixed between two consecutive computational steps.



$$Cvol_{i,1} = l_1 \frac{(C_i - C_1)}{d_1} \frac{(h_i + h_1)}{2} \Delta t D + \begin{cases} Fvol_1 C_1 \ for \ Fvol_1 < 0 \\ Fvol_1 C_i \ for \ Fvol_1 > 0 \end{cases} \quad (1)$$

$$\Delta C_i = \frac{1}{A_i h_i} \sum_{n=0}^{n=3} Cvol_j \quad (2)$$

Figure 1. A schismatic of a computational cell j and its neighboring cells (1,2 and 3)

The pollutant concentration in a Brezo computational cell (**Figure 1**) is determined by volume of pollutant-flow, *Cvol*, across cell faces, obtained using advection-dispersion relationship as in **Equation (1)** where h_i is the water depth of the cell *i*, *D* is the diffusion coefficient and Δt is the time step and Fvol is the fluid volume flow across the boundary. The first term on the left represents dispersion and second advection. The total change in of concentration change over a time step in the triangular cell is obtained by **Equation (2)**.

Due to the finite size of computational cells, the numerical scheme adds a implicit amount of diffusion to the simulation. This is related to the size of the computational cell and we estimated this using idealized studies, a explained below.

Modelling Results

First, we tested the developed pollutant transport model using under steady hydraulic conditions, using an idealized 100m x 100m flood plain under constant lateral velocity of 1 cm/s and water depth of 1 m. Within flood-plain area, we released a pulse-concentration of 1 mg from a point source at x=30,y=50. The analytical solution for such a pulse-release is given by:

$$C(x,y,t) = \frac{M/L_z}{4\pi(t-t_0)\sqrt{D_x D_y}} exp\left[-\frac{\left(x-x_0-u(t-t_0)\right)^2}{4D_x(t-t_0)} - \frac{\left(y-y_0-v(t-t_0)\right)^2}{4D_y(t-t_0)}\right] \tag{3}$$

where M/L is mass per unit depth (of flow) released at location (x_0; y_0) and at time t_0. Dx and Dy are the diffusion coefficient in x and y direction, respectively. u and v represent velocity in x and y direction (Huber, 1992). The model was calibrated with the analytical result at time 54min and was validated at 18min and 74min. (**Figure 2**). Then the model was validated by comparing simulated and analytical concentrations at other time steps (180min and 240min).

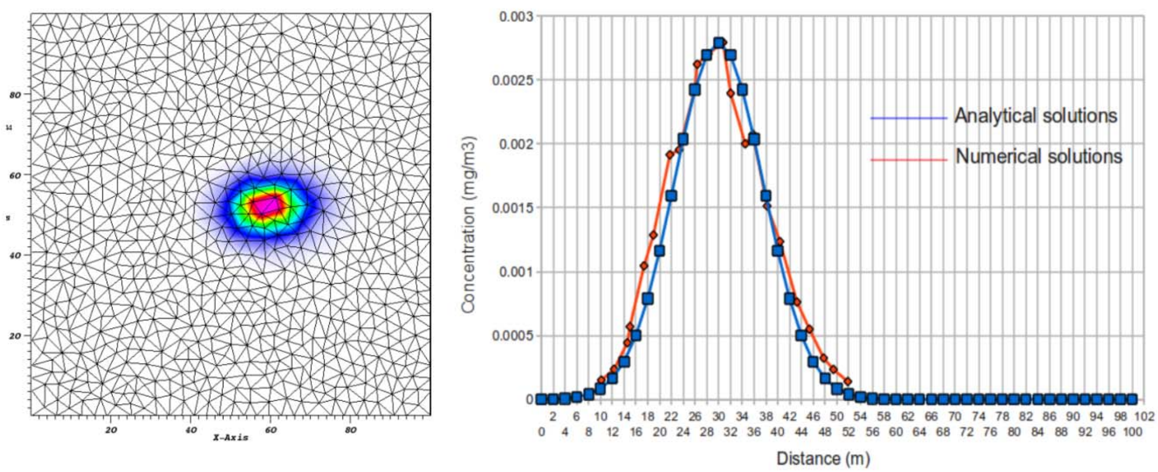


Figure 2. Instantaneous point source simulation. The pollutant concentrations at 54min (left). Modelled and observed concentrations at 18min after release (right).

Figure 3 shows the second ideal simulation (continuous source) used to validate the model under the same flow condition as above. In this case we used different y-y cross sections for calibration and validation.

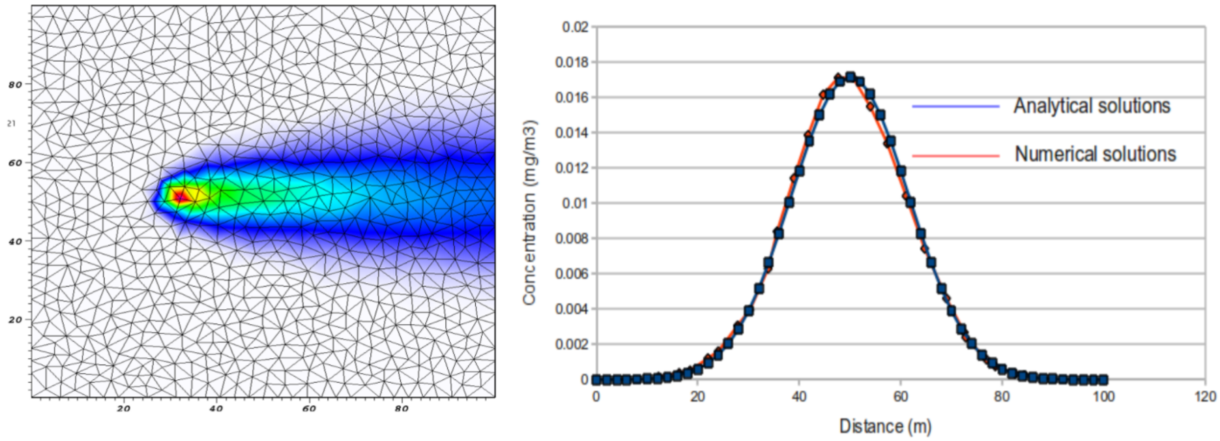


Figure 3. Continuous point source simulation (left) and model validation (right)

Due to the finite size of computational cells together with assumption of being well-mixed within the cell, the numerical scheme introduces a degree of pseudo-diffusion that depends on the computational cell size. Hereafter we call this value `implicit diffusion coefficient'. We used idealized simulations with different computational cell sizes. As shown in **Figure 4**, the relationship of Implicit D.C. to `length' (Square-root of area) of the computational cell is linear. When the model is used in practice, attention should be paid to this relationship.

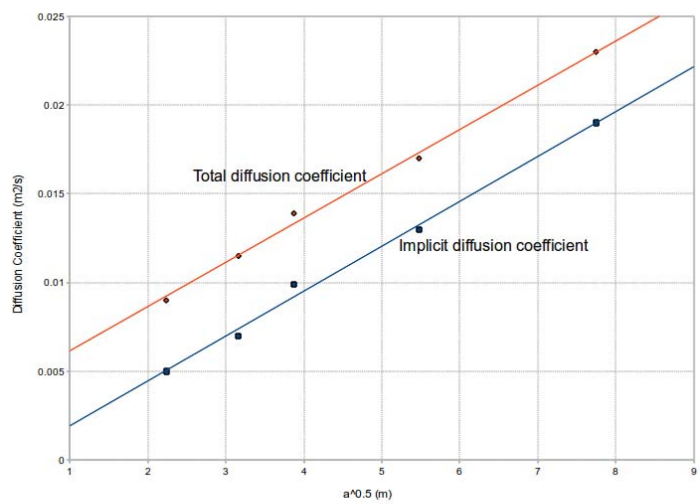


Figure 4. Relationship between implicit and total diffusion with cell sizes. (e.g. If diffusion C. to be modelled is 0.017 and cell size (Square-root of the area) is 5 then the `explcit' (specified) d.c. should be set to 0.004, because implicit d.c. is 0.013 for cell size 5).

Next, we present the results of an idealized study conducted to test the 1D/2D integration of pollutant transport. The essential details of the modelling domain is shown in figure x. The purpose of this case is to verify the 1D/2D interaction of water and pollutant. However, for the `validation' of this case we had to solely rely on our judgement as there was no field measurements or experimental data to validate this.

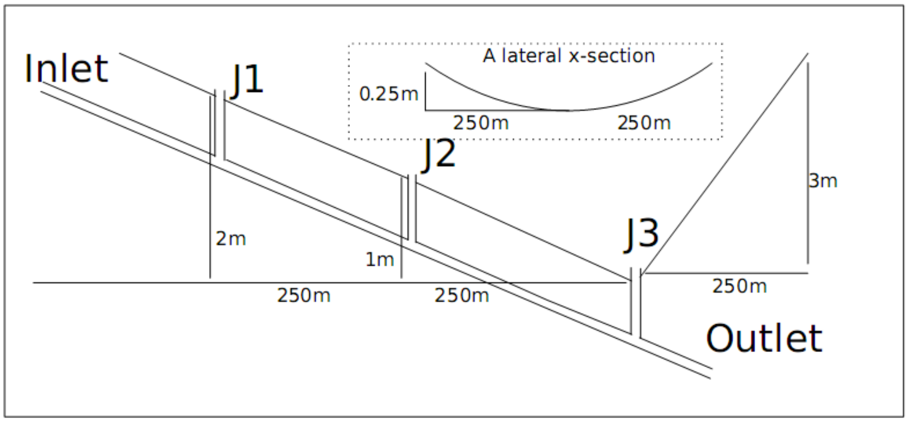


Figure 5. The idealized flood-plain. Vertically exaggerated (x100).

The domain was discretized with triangular cells of average size 100 m^2. The inflow hydrograph (at 'Inlet') was a simple triangular shaped pulse lasting about 20min with peak flow of 22 m^3/s.

The model results show that the interaction between sewer and overland flow was successfully simulated during simulation (**Figure 6**). The simulation clearly shows the rise (1D to 2D flow from J1) and fall (return flow from 2D to 1D at J3) of inundation depth in the flood plain.

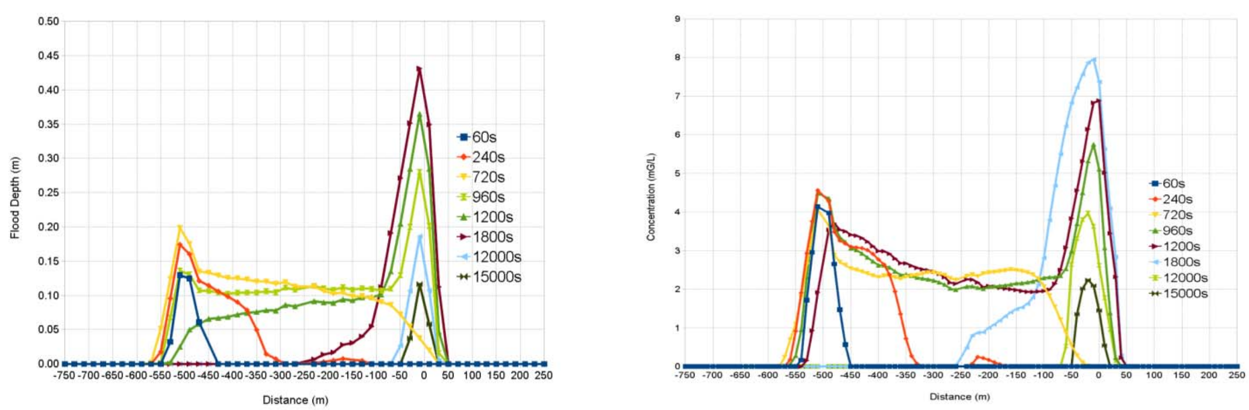


Figure 6. Flood depth variation (left) and concentration variation (right)

1. Garforth case study

The developed model was applied in Garforth, UK, which has been affected by several flood events since the 1980s (DEFRA, 2008). The area is divided into two parts known as the Central Catchment and the Southeast Catchment with their own urban drainage system. In this case study, we modelled the Central Catchment with total area of 71 ha. The drainage model consists of 88 nodes within 72 sub-catchments. We discritized the flood-plain using a DEM of resolution, 4m x 4m to create a triangular cell of average area 8 m^2. The design storm of 30 years 90 minutes from previous study (Delelegn et al., 2011) was used as an input for the catchment models. The drainage system in Garforth is in a separated system. We considered a hypothetical cross contamination that releases 300 mg/l for a period of 1 hour after the start of the simulation at an upstream location (figure 5). The diffusion coefficient was assumed to be 0.06 m^2/s (Since the implicit d.c. for the 8 m^2 cell size is 0.006 m^2/s, the explicit d.c. should be 0.05 m^2/s). In reality diffusion coefficient depends on a number of parameters like flow velocity, channel width, water depth, wind and vertical turbulence (Benkhaldoun et al., 2007), but is extremely difficult to accurately estimate in catchment-scale studies like this. Therefore keeping d.c. constant in this study, while being a source of error, is justified.

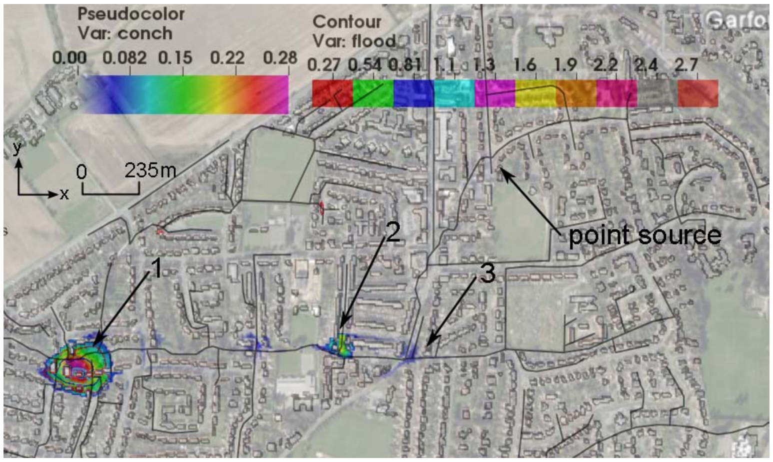


Figure 7. Simulation result for Garforth case study (Contours: inundation, Color gradients: pollutant mass per m2)

During 5 hours of simulation time, the model showed its ability to model pollutant transport in the complex urban drainage network. There are three main locations that are prone to flooding in the network (**Figure 7**). After 2 hours, peak of pollutant concentration at location 3 was 1.2 mg/m^2, while pollutant concentration at location 2 and 1 were 1.0 mg/m^2 and 0.75 mg/m^2, respectively. At the end of simulation, the most polluted area was observed at location 1 with peak of pollutant concentration 0.3 mg/m^2, while concentration at location 3 decreased to 0.04 mg/m^2. While the main conveyance of pollutant was the drainage network, it was observed that a fraction was also transported in overland flow and re-introduced to the sewer system as given in **Figure 8** for location 1.

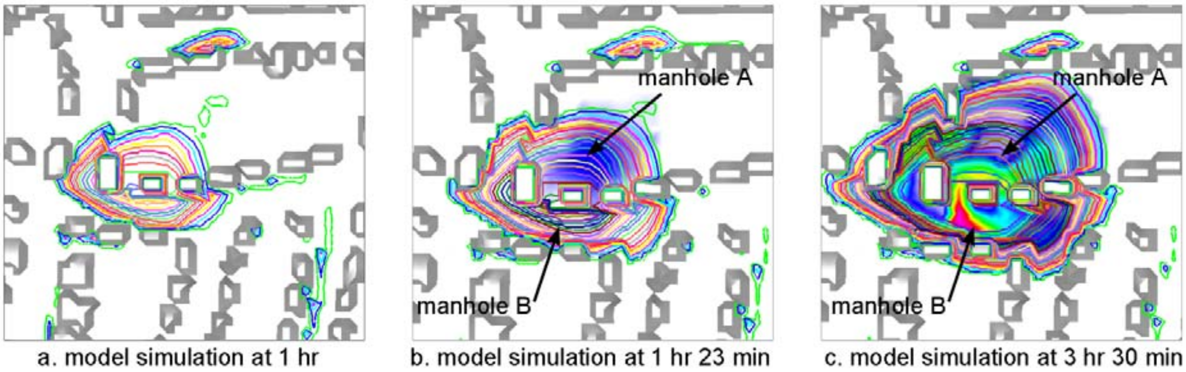


Figure 8. Pollutant transport at location 1 at several time simulation. (Contours: inundation, Color gradients: pollutant mass per m^2)

Figure 8 shows that 2D transport process was started once the manhole was surcharged carrying pollutant on the ground. Pollutant movement was driven by advection conveying the pollutant in x-y direction following flood flow which is indicated by flood contour. The figure also shows that peak of concentration at some locations in downstream area can be influenced by diffusion process (Yan and Kahawita, 2000) which dominates the transport process when the flow becomes laminar (Huber, 1992) -- the probable surface-flow regime during late part of the simulation.

2. Can Tho case study

Can Tho City is the center of the Mekong Delta which is located about 135 km southwest of Ho Chi Minh City, Vietnam. Located next to the Hau River, the total area of Can Tho is 1,401 km^2 divided into four urban districts and four mainly rural districts. This area was suffering from flood events on October 5, 2009, recorded as the largest flooding event in Can Tho. The recorded rainfall data on the flooding day with highest intensity of 44 mm/hr was used as an input rainfall time series in SWMM. In this case study, we were compelled to use a lower resolution DEM of 15m x 15m which was then used to create triangular cell with average area 30 m^2. We used this cell area information to specify explicit diffusion 0.05 m^2/s from (**Figure 4)** since we assumed to use real diffusion coefficient 0.063 m^2/s. Compared to Garforth, the drainage system in Can Tho is highly polluted under normal conditions. We represented this situation by assuming that each ha of sub-catchment area as producing 100 mg/s dry weather concentrations. The drainage system around the flood-prone area has 52 nodes and 41 sub-catchments totalling an area of 240.58 ha. The model was simulated for 11 hours. During simulation, the model showed flow exchange as well as process of pollutant transport in overland flow as given in **Figure 9** and **Figure 10**.

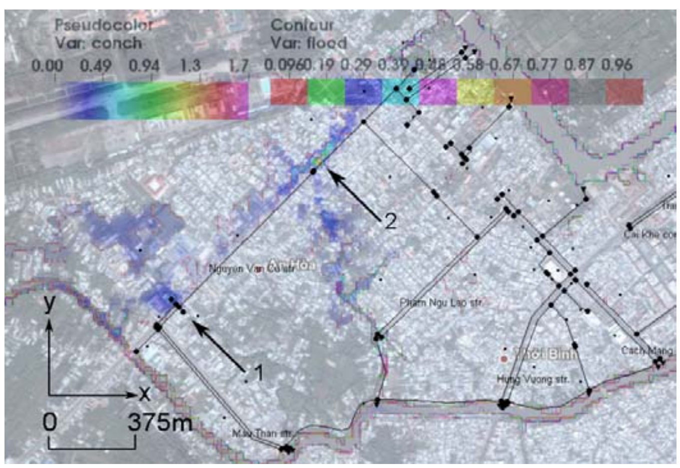


Figure 9. Simulation result for Can Tho case study

It was observed that pollutant concentration, 0.3 mg/m^2, was initially observed on the ground at location 2 after 1 hour of simulation and it then moved across the area toward lower elevation points. The most polluted location after 2 hours was predicted at location 1 with peak of pollutant concentration at 0.8 mg/ m^2, while peak of concentration at location 2 was increased to 0.5 mg/m^2. Peak of pollutant concentration at two observed locations were significantly changed after 5 hours. At this time step, peak of pollutant concentration at location 2 reached the highest level at 1.7 mg/m^2 and then decreased gradually to 0.5 mg/m^2 at the end of simulation. On the other hand, peak of concentration at location 1 kept decreasing from 0.5 mg/m^2 at t = 5 hour to 0.04 mg/m^2 at t = 11 hour.

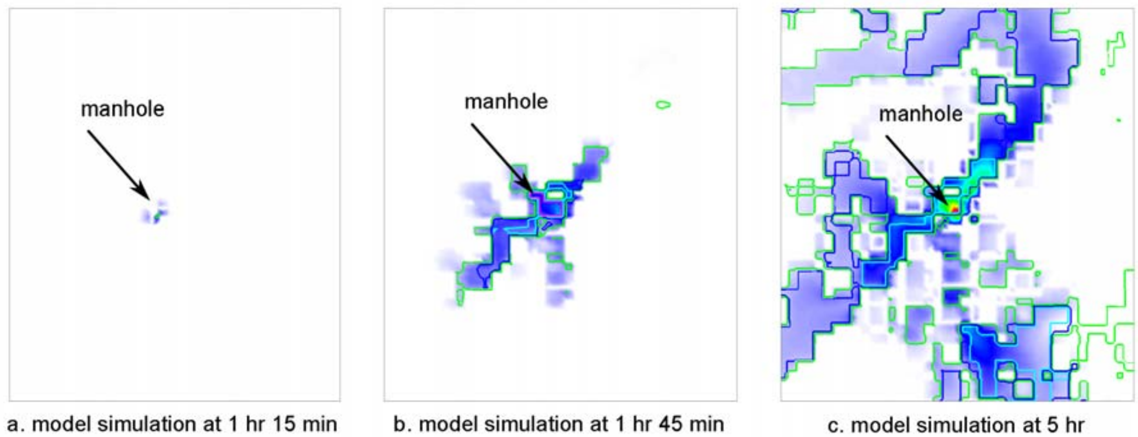


Figure 10. Pollutant transport at location 2 at several time simulation. (Contours: inundation, Color gradients: pollutant mass per m^2)

This case study clearly demonstrated the importance of high DEM resolution to make quality inundation predictions in plain areas. At a low DEM resolution as 15m x 15m, many important urban topographical variations are ignored and the land is perceived as smoother and more regular than it really is. This is clearly demonstrated by the patchy nature of inundation contours and concentration gradients in **Figure 10**. This condition might result in accumulated water and concentration at some location having significant distance to the manholes.

Conclusion

In this research, a two-dimensional pollutant transport model has been developed and applied in a number of case studies. The model could simulate the exchange of hydraulic and scalar quantities between 1D and 2D systems in a convincing manner. The model is developed by implementing advection diffusion relationship at boundaries of each computational cell. The cells were assumed to be fully mixed. As commonly observed in finite cell-based numerical schemes, the model demonstrated a degree of `implicit' diffusion whose diffusion coefficient increased linearly with cell length. As demonstrated by two case studies, the model works well for sewer-overflow cases involving fairly complex 1D networks and varying 2D topography, including buildings. We observed that the accuracy of the 2D model depends largely on the quality and precision of the topographic data. In the case of Garforth, UK, we had access to excellent topographic information derived from LIDAR sources. For Can-tho, Vietnam, the topography was much cruder. Together with the fact that Can-Tho is a much more flatter terriain compared to Garforth, this led to spurious rectangular patterns in the inundation heights and pollutant loadings (Figure 10). The model is suitable for simulating dissolved pollutants during short urban floods. Much research need to be done to calibrate and validate the 1D/2D coupling of the model. It is planned to use scale-model experiments to achieve this goal in the future.

References

Begnudelli, L., Sanders, B.F., 2006. Unstructured Grid Finite-Volume Algorithm for Shallow-Water Flow and Scalar Transport with Wetting and Drying. Journal of Hydraulic Engineering, ASCE, 132(4): 371-384.

Benkhaldoun, F., Elmahi, I., Seaid, M., 2007. Well-balanced finite volume schemes for pollutant transport by shallow water equations on unstructured meshes. Journal of Computational Physics, 226: 180-203.

Butler, D., Davies, J.W., 2004. Urban Drainage.

DEFRA, 2008. WEST GARFORTH INTEGRATED URBAN DRAINAGE PILOT STUDY : FINAL REPORT.

Delelegn, S.W., Pathirana, A., Gersonius, B., Adeogun, A.G., Vairavamoorthy, K., 2011. Multi-Objective optimisation of cost-benefit of urban flood management using a 1D2D coupled model. Water Science and Technology: 1053-1059.

Diaz-Fierros, T.F., Puerta, J., Suarez, J., V., F.D.-F., 2002. Contaminant loads of CSOs at the wastewater treatment plant of a city in NW Spain. Urban Water, 4: 291-299.

Hood, M., Reihan, A., Loigu, E., 2007. Modeling urban stormwater runoff pollution in Tallinn, Estonia.

Huber, W.C., 1992. Contaminant Transport in Surface Water. In: Maidment, D.R. (Ed.), Handbook of Hydrology. McGraw-Hill, pp. 14.1 - 14.50.

Passerat, J., Ouattara, N.K., Mouchel, J.-M., Rocher, V., Servais, P., 2010. Impact of an intense combined sewer overflow event on the microbiological water quality of the Seine River. Water Research.

Ramaswami, A., Milford, J.B., Small, M.J., 2005. Integrated Environmental Modeling

Rossman, L.A., 2010. Storm Water Management Model 5.

Semadeni-Davies, A., Hernebring, C., Svensson, G., Gustafsson, L.-G.A.r., 2008. The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: Combined sewer system. Journal of Hydrology, 350: 100- 113.

UN-HABITAT, 2010. State of The World's Cities 2010/2011 : Bridging The Urban Divide. UN-HABITAT.

Yan, M., Kahawita, R., 2000. Modelling The Fate of Pollutant in Overland Flow. Water Research, 34(13): 3335-3344.

Zoppou, C., 2001. Review of urban storm water models. Environmental Modelling & Software, 16: 195-231.