COMBINING TWO ALGORITHMS AS A TRANSITION RULES FOR CA-BASED INUNDATION MODEL

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ABSTRACT

Emergency operations aim to reduce or mitigate the impacts of disasters. To support these priorities, sufficient lead time is an important consideration. Rapid inundation simulation for an early flood warning system considers as an effective with high-resolution of Digital Elevation Model (DEM). Flood model based on Cellular Automata (CA) is a model that does not solve the complex governing equations to generate inundation map. Many studies have proven its advantages of efficiency and accuracy in flood simulation. This paper develops a CA-based inundation model to meet the need of rapid flood response. Different from other CA-based models, this study introduced the combination of minimization algorithm and simplified weighting algorithm for flood routing. One case is performed to test the performance of the new CA-based inundation model. The case study is a benchmarking 2D hydraulic modelling packages case number 8A published by the Environment Agency Government of the United Kingdom. This case is used to analyze the surface flow in an urban area with rainfall and point source as the main inflow. The model's result was compared with TUFLOW. The results showed that the proposed model has good agreement in the inundation extend with the TUFLOW's result. However, the inundation depths are slightly underestimated and there is considerable room for improving the computation times.

Keywords: Cellular Automata, Rapid Inundation Model, Early Warning System

1. INTRODUCTION

Flood is one of the major natural hazards. It happens due to several reasons such as river overflows, high rainfall intensity, storm surges and topography issues. Within the highly populated area, the casualties and financial losses caused by the flood are inevitably massive. Based on those reasons, the mitigation of urban flooding hazards becomes very crucial. To support that, a robust and efficient model to predict the flood inundation is necessary. Two dimensional hydraulic modeling to predict inundation in urban areas has become an important research topic in recent years. Its improvement in performance is increased by the advancement of computational resources (e.g. parallel computing and GPUs), together with the increasing availability of high-resolution Digital Elevation Model (DEM) such as light detection and ranging (LiDAR) surveys (Hunter, et al., 2008; Schubert et al., 2008).

Flood risk analysis in urban areas requires accurate predictions of flow velocities and water depths. Hence, 2D models based on the full shallow water equations (SWEs) are recommended and often used (Cunge, 2003). However, due to its complexity these kinds of models become computationally expensive and require longer computation time. In order to reduce the computation time, some models try to reduce the complexity of the equations or neglecting less significant terms of the equations (Bates, 2000). Moreover, many new models are developing based on simplified assumptions (Chen et al., 2007; Bates et al., 2010) or using very different fundamental approach(Lhomme et al., 2009; Dottori and Dotini, 2011; Ghimire et al., 2013; Yang et al., 2015).

Cellular Automata (CA) is discrete and abstract computational systems introduced by Wolfram (1984). Some studies showed that this kind of models provides reliable results with shorter computational time compared to other the models that solve SWEs. Naturally, CA is implementable trough parallel computing, which allowed for more efficient simulations. Moreover, the running simulation of CA is based on a regular square grid, hence, it could save set-up time to change from terrain data into mesh-grid. The important component of the CA-based model is the transition rule which indicates the movement or distribution of flood water. There are many transition rules that have been developing (Liu et al, 2015; Guidolin et al., 2016; Jamali et al., 2019). Furthermore, this paper develops a CA-based inundation model by combining the minimization algorithm (Di

Gregorio et al, 1999) and a simplified weighting algorithm. The results from this model are compared to the well-known 2D hydrodynamic model TUFLOW.

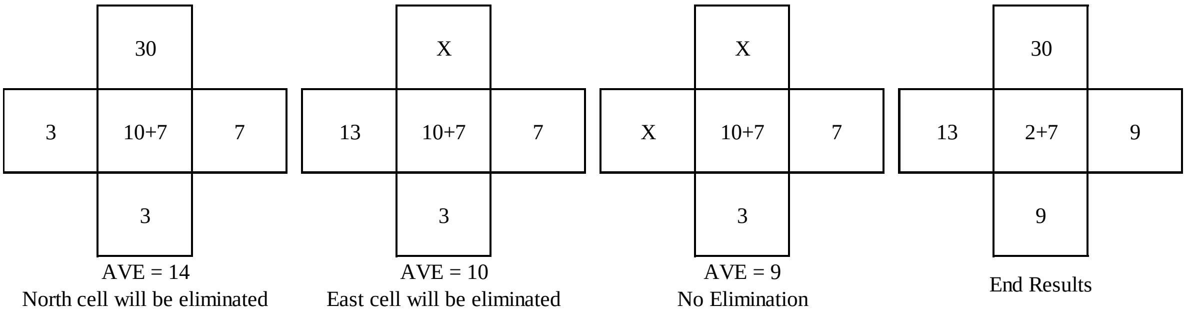
2. MODEL DESCRIPTION

The model consists of three major parameters that could be seen at Eq. (1).

$$CA = (W, NH, T) \tag{1}$$

World (W) define as lattice space where the calculation took place. For inundation model, lattice space could be describe as DEM and regular square grid is being used to discretize the domain. The Von Neumann neighborhood system (NH) is used in this model. This system allows the water moves from central cell to the other four cells orthogonally at each iteration. Transition rules (T) are set of rules to determine how the water will move for each iteration. This model uses a combination of minimization algorithm and simplified weighting to spread the water.

Liu et al. (2015) uses the minimization algorithm, proposed by Di Gregorio and Serra (1999), to spread the water from central cell to the neighborhood system. The rules start from averaging the water surface elevation of the neighborhood system, including the central cell, and then eliminating the cell that higher than the average (AVE). Recalculate the AVE, excluding the eliminated cell(s), and repeat the steps until no more cell is eliminated. The water surface elevation of the remaining cell(s) will be equal to the AVE (equilibrium state).



* Central cell ground elevation (z) = 7 and water depth = 10, AVE (Average)

Figure 1. Illustration of the minimization algorithm.

In some cases, the water within central cell is not sufficient to be spread to the NH system. This is one of the drawbacks from minimization algorithm. In order to solve this problem, this study add another algorithm. Simplified weighting algorithm (SWA) is a simplification from the weighting system proposed by Guidolin et al. (2016). SWA was introduced by Jamali et al. (2019) but in this case the parameter h_f (friction loss) is neglected. Instead of using the volume, this study uses water depth as a trigger. The algorithm will be applied if the water volume at central cell is not sufficient to be spread to reach the equilibrium state using the minimization algorithm. This algorithm will spread the water from central cell to the lower elevation neighbor cell(s). The formula for the algorithm could be seen below (Eq. (2) and Eq. (3)).

$$Y = \max\,(0, H_0 - H_i) \tag{2}$$

$$AV_i \; = AV_i \; + \frac{Y_i}{\sum_{i=1}^{4} Y_i} x\, AV_0 \tag{3}$$

Y denotes the difference of water surface elevation between central cell (H_0) and its four neighboring cells ($H_{i,\ i=1,2,3,4}$). The Eq. (2) shows that the water will only flow to the lower elevation. If the neighbor’s water elevation is higher than the central cell water elevation the Y will be equal zero. Available Volume (AV_i) denotes the total volume of water in one cell and AV_0 denotes the available water in central cell. AV_0 will be distributed to the downstream cell(s) based on the proportion shown in Eq. (3) and leaves nothing at the central cell. In other words, after this algorithm has been applied the AV_0 will be equals to zero.

3. CASE STUDY AREA

The model is tested using a Test 8a from the EA (Environment Agency) Benchmark Study (Neelz and Pender, 2013). The modelled area is approximately 0.4 km^2 with average slope 4.3% and the ground elevation range from 21 – 37.6 m. The DEM is a 0.5 m resolution DTM (no vegetation or buildings) created from LiDAR data collected on 13 August 2009 and provided by the EA (http://www.geomatics-group.co.uk). The terrain could be seen from the figure below (Fig. (2)).

The boundary condition is set to be closed boundary and the initial condition is dry bed. There are two types of inflow in this case. First the point source inflow with the maximum discharge is 5 m^3/s and location of the source is shown in the Fig. (2). Beside the point source, there are inflows from the uniform rainfall. The rain lasts for 3 minutes with the rainfall intensity equals to 400 mm/hr.

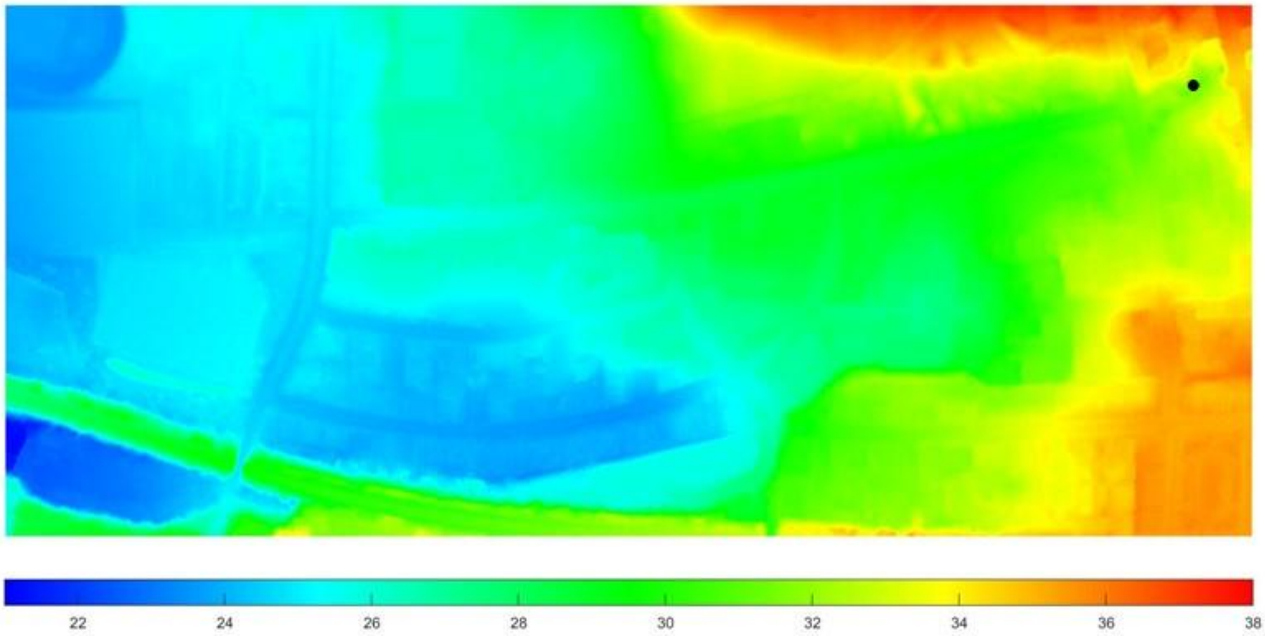
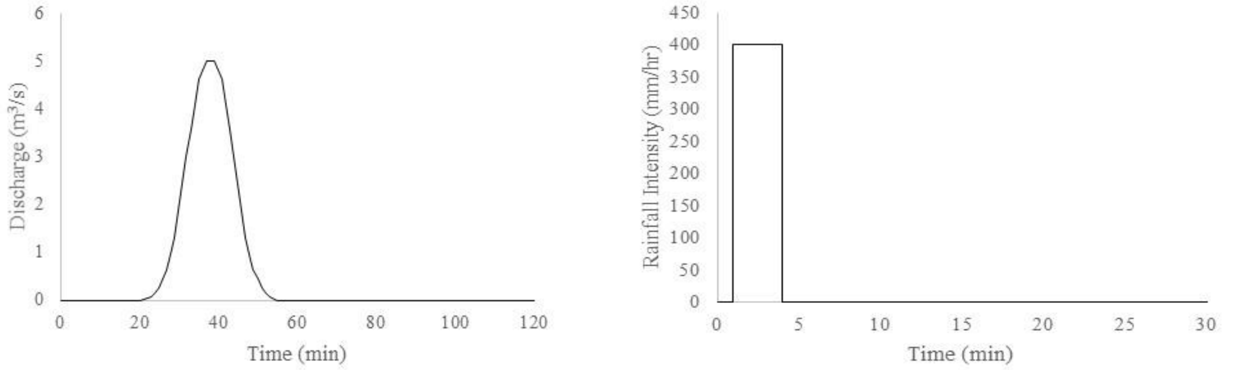


Figure 2. Study area (black dot indicates the inflow location)



(a) (b)

Figure 3. (a) point source inflow (b) rainfall intensity

To compare the performance of the proposed model with TUFLOW, three common model performance indicators are used to compare the results (Bennett et al., 2013): (i) Root Mean Square Error (RMSE), (ii) True Positive Rate (TPR), and (iii) False Discovery Rate (FDR). The RMSE could be calculated using the Eq. (4) where X_i is the *i*-th cell of the water depth produce by TUFLOW, Y_i is the *i*-th cell of water depth of the model result, and n is the total number of cells. In calculating RMSE cells will be considered wet if the water depth at *i*-th cell greater than the threshold either proposed model or TUFLOW. The threshold is set into several value (0.05 m, 0.1 m, 0.2 m, and 0.3 m).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{n}} \tag{4}$$

The TPR/Hit Rate and FDR/False Alarm Rate are used to compare the inundation area by the two models. True Positive (TP) denotes the number of cells that both models identified as wet. False Negative (FN) is the total number of cells that the proposed model identified as dry while TUFLOW identified as wet. False Positive (FP) represents the number of cells that proposed model identified as wet while TUFLOW identified as dry. Last, False Negative (FN) represents the number of cell that proposed model identified as dry but the TUFLOW identified as wet. The equation of TPR and FDR could be seen at Eq. (5) and Eq. (6).

$$TPR\ (\%) = \frac{TP}{TP + FN} x100 \tag{5}$$

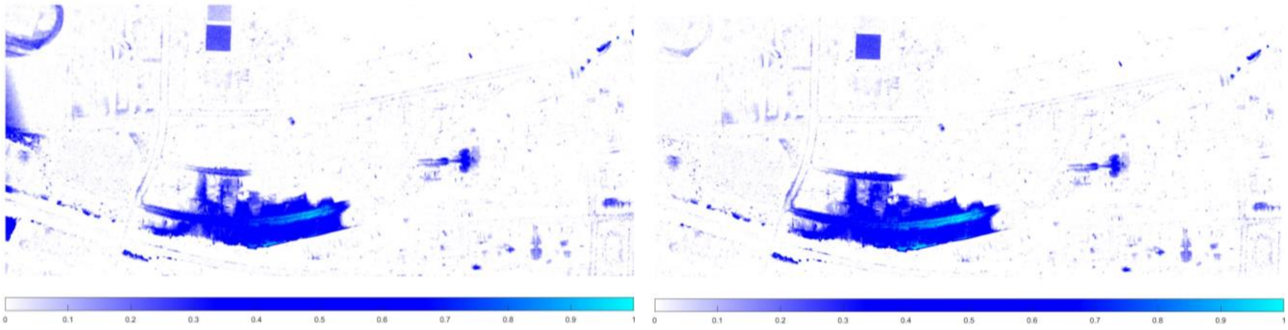
$$FDR\ (\%) = \frac{FP}{TP + FP} x100 \tag{6}$$

4. RESULTS AND DISCUSSION

Based on the report (Neelz and Pander, 2013), the case study should be run until t (time) reach the 5 hours to make sure the water reaches the equilibrium state. Since the proposed model is a CA-based model, it means that the water level will evolve every iteration. Unfortunately, this iteration step does not equal to time step (dt). In other words, the model could not give time varied results. Hence, the user must provide adequate numbers of iteration for the model to simulate in order to reach the equilibrium state result. In this case study, based on the trial and error, 150,000 iterations are required for the model to reach equilibrium state.

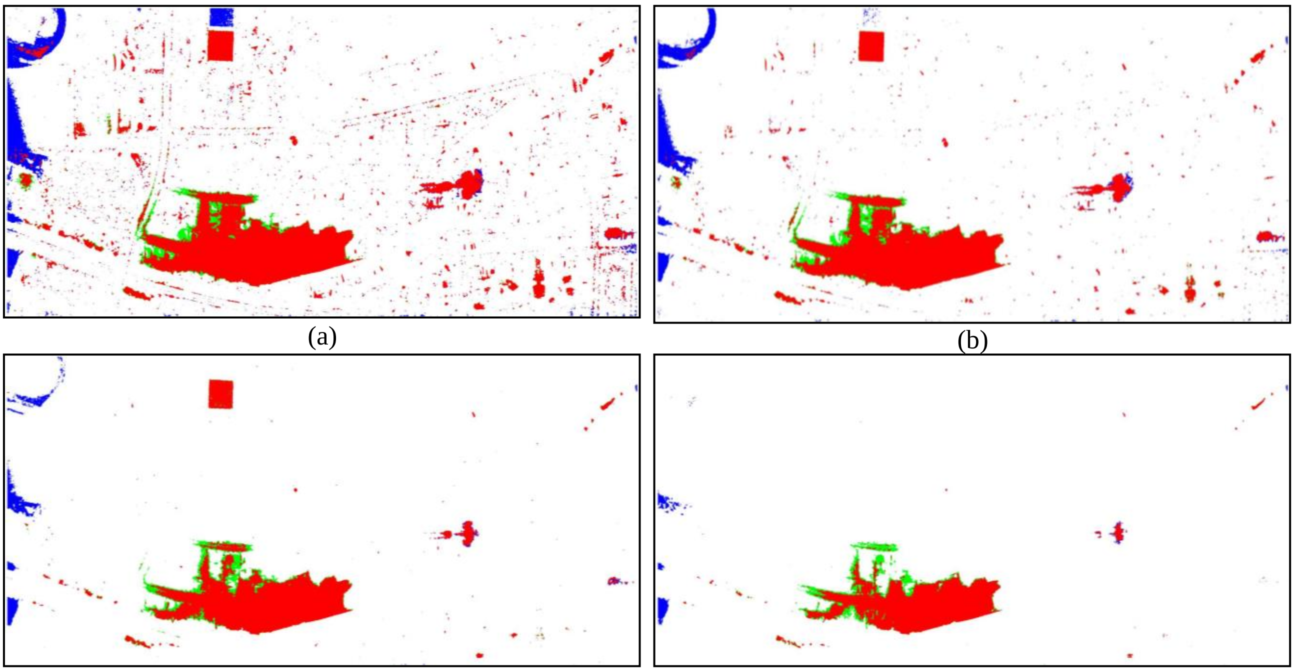
Unlike TUFLOW, the major driven force of water movement in the proposed model is gravity. In other words, the water will be moved to the lower ground. In this case study, the water accumulated in the lower ground (blue area in the Fig. 2). Based on the results (Fig. 4 (a)), the model produces inundation map as predicted. All the water is accumulated in the lower elevation area. Visually, the inundation map generated by the proposed model and TUFLOW is quite different especially in the eastern part of the area. TUFLOW shows no significant inundation eastern area. However, at the middle area where the most severe flooding area occurs both models show similar inundation pattern.

Fig. (5) shows more detail comparison between two models. The figures shown the overlapping inundation areas produces by the two models at different threshold. Red color indicates the overlapping inundated area, the flooding areas simulated from proposed model and TUFLOW are “dark blue’ and “green”, respectively. From these figures, both models generated inundation at the central area for various threshold values. However, it can be seen that the TUFLOW produced slightly higher inundation depth compared with proposed model. It proved by the decreasing of red color area at the central area for higher threshold value.



(a) (b)

Figure 4. The comparison of modeling results from (a) the proposed model from this study and (b) TUFLOW



(a) (b)

(c) (d)

Figure 5. Overlapping inundation area (red color) between proposed model (blue color) and TUFLOW (green color) (a) threshold = 0.05 m (b) threshold = 0.1 m (c) threshold = 0.2 m (d) threshold = 0.3 m.

Table 1. shows the value of RMSE, TPR, and FDR of various threshold values. Based on the results, RMSE value range from 0.1 – 0.15 m. It means, there is still some error between those two models but the error values are near the optimal value of RMSE. As it mentioned before, the larger contributor to this error is probably the difference accumulated water in the left area. Since the proposed model shows some accumulated water in those areas, it causes the water depth at central area is much lower compare to TUFLOW.

From the previous section, the TPR and FDR are used to compare the inundation extend between these two models. Based on the results, the TPR value range from 81.12 % - 89.96% (optimal value TPR = 100%). It means the proposed model predicts over 80% of the area that identified by TUFLOW. Moreover, FDR result shows the percentage of area that is not inundated from the perspective of TUFLOW's result but it is inundated from the proposed model. The result shows the 20.31% of the area is over-predicted by the proposed model when the threshold is 0.05 m. In conclusion, it shows that there is a good agreement in the inundation extend between two models.

Table 1. Performance indicator results for various threshold values

Performance Indicator	**Threshold**				**Range**	**Optimal Value**
	0.05 m	**0.1 m**	**0.2 m**	**0.3 m**		
RMSE	0.112	0.128	0.140	0.149	0-∞	0
TPR	89.96	88.67	85.45	81.12	0-100%	100%
FDR	20.31	17.65	10.94	6.39	0-100%	0%

In term of the computational time, the proposed model is faster compare to TUFLOW. TUFLOW needs 21 hours to finish the computation under GPU scheme while the proposed model requires 5 hours to finish the computation.. Although the proposed model works faster than TUFLOW, it is still not fast enough for the emergency responses. Long computation time for proposed model caused by the large number of iterations. As a preliminary work, the proposed model shows its potential to serve as a tool for rapid assessment of flood hazard, however, it requires a lot of improvement especially to increase the accuracy and computation efficiency.

5. CONCLUSIONS

The main idea of this paper is to see whether the combination of two algorithms could be used as efficient transition rules for CA-based inundation model. The results showed that the proposed model has good agreement in the inundation extend with the TUFLOW's result. From the RMSE value it could be seen that the maximum error is 0.149 m when the threshold is 0.3 m. Based on the TPR value, the hit ratio of the model is very good. For all the threshold value, the hit ratios are all above 80%. In the perspective of FDR value, the proposed value also performs very well. None of the value from any threshold value gives number higher than 20% except when the threshold equals to 0.05 m. The proposed model shows a good comparison with the TUFLOW model in terms of the predictions of flood extent. However, the proposed model still needs a lot of improvements in terms of computation speed and accuracy of the model. Moreover, the model could not give time varied results that will help decision-making and it will be included in the future.

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REFERENCES

Bates, P.D., Horrit, M. S., and Fewtrell, T. J. (2010). A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. *Journal of Hydrology,* 387(1-2), 33-45.

Chen, A. S., Djordjevic, S., Leandro, J., and Savic, D. (2007). The urban inundation model with bidirectional flow interaction between 2D overland surface and 1D sewer networks. *NOVATECH 2007.*

Cunge, J. A. (2003). Of data and models. *Journal of Hydrodynamics,* 5(2): 75-98.

Di Gregorio, S., and Serra, R. (1999). An empirical method for modelling and simulating some complex macroscopic phenomena by cellular automata. *Future Generation Computer System*, 16:259-271.

Dottori, F., and Todini, E. (2011). Developments of a flood inundation model based on the cellular automata approach: Testing different methods to improve model performance. *Physics and Chemistry of the Earth Parts A/B/C*, 36(7): 266-280.

Ghimire, B., Chen, A. S., Guidolin, M., Keedwell, E. C., Djordjevic, S., and Savic, D. A. (2013). Formulation of a fast 2D urban pluvial flood model using a cellular automata approach. *Journal of Hydroinformatics*, 15(3): 676-686.

Guidolin, M., Chen, A. S., Ghimere, B., Keedwell, E. C., Djordjevic, S., and Savic, D. A. (2016). A weighted cellular automata 2D inundation model for rapid analysis. *Environmental Modelling and Software*, 84: 378-394.

Hunter, N. M., Bates, P. D., Neelz, S., Pender, G., Villanueva, I., Wright N. G., Liang, D., Falconer, R. A., Lin, B., Waller, S., Crossley, A. J., and Mason, D. C. (2008). Benchmarking 2D Hydraulic models for urban flooding. W*water Management*, 161: 13-30.

Jamali, B., Bach, P. M., Cunningham, L., and Deletic, A. (2019). A Cellular Automata fast flood evaluation (CA-ffe) model. *Water Resources Research*, 55:4936-4953.

Lhome, J., Sayers, P., Gouldby, B., Samuels, P., Wills, M., and Mulert-Marti, J. (2009). Recent development and application of a rapid flood spreading method. *Flood Risk Management: Research and Practice*, pp 15-24.

Liu. L., Liu, Y., Wang, X., Yu, D., Liu, K. Huang, H., and Hu, G. (2015). Developing an effective 2-D urban flood inundation model for city emergency management based on cellular automata. *Natural Hazards and Earth System Science*, 15:381-391.

Neelz and Pender. (2013). *Benchmarking the last generation of 2D hydraulic modelling packages* (SC120002). Retrieved from Environment Agency.

Schubert, J. E., Sanders, B. F., Smith, M. J., and Wright, N. G. (2008). Unstructured mesh generation and landcover-based resistance for hydrodynamic modeling or urban flooding. *Advances in Water Resources*, 31: 1603-1621.

Wolfram, S. (1984). Cellular automata as models of complexity. *Nature*, 311: 419-424.

Yang, T. H., Chen, Y. C., Chang, Y. C., Yang, S. C., & Ho, J. Y. (2015). Comparison of different grid cell ordering approaches in a simplified inundation model. Water, 7(2), 438-454.