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Thrysøe, Cecilie; Toke, Jens; Borup, Morten; H. Ravn, N. ; Arnbjerg-Nielsen, Karsten

Published in:
Proceedings of 9th International Conference on Planning and Technologies for Sustainable Urban Water Management

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Developing Fast and Reliable Flood Models

Développement de modèles d'inondation rapides et fiables

C. Thrysøe*, J. Toke*, M. Borup*, N. H. Ravn**, K. Arnbjerg-Nielsen*

*Technical University of Denmark, Department of Environmental Engineering, Miljøvej, 2800 Kgs. Lyngby, Denmark. cethry@env.dtu.dk
**LNH Water, Kathøjvej 3, 3080 Tikøb, Denmark. nanna@lnhwater.dk

RÉSUMÉ

L'état de l'art de la modélisation d'inondations en milieux urbains est basé sur des modèles détaillés utilisant des critères physiques. Cependant, leur utilisation est bridée par les exigences de temps de calcul et les instabilités numériques. Les calculs sont donc longs et difficiles. Pour surmonter ces difficultés, nous avons développé et testé des modèles de substitutions simplifiés (surrogates) d'exécution plus rapide, dont le but est de calquer la réponse du modèle d'origine. Le modèle de substitution est construit en compartimentant le model d'origine; chaque compartiment correspond à une zone confinée pour laquelle le volume est modélisé. Nous avons développé deux types de simplifications: (i) Le système d'assainissement est modélisé par une surface de réponses générée par un modèle empirique utilisant des données de mesure. (ii) Les écoulements de surface sont modélisés en utilisant une fidélité physique moindre basée les dépressions de surface et les voies d'écoulement. Ce modèle de substitution est testé à Aarhus, Danemark, et remplace les composants d'un modèle MIKE FLOOD. Les simplifications du system d'assainissement sont capables de reproduire les résultats obtenus avec MIKE URBAN pour l'ensemble des pluies testées. L'interface canalisation-surface du model simplifié est limitée par le manque de détails de l'écoulement de surface ce qui réduit la précision du model. Le modèle ne montre aucun signe d'instabilité, permettant des intervalles de temps plus longs, ainsi le temps de calcule peut être réduit par un facteur de 1400. Les modèles de substitutions démontrent un grand potentiel pour la modélisation en hydrologie urbaine.

ABSTRACT

State-of-the-art flood modelling in urban areas are based on distributed physically based models. However, their usage is impeded by high computational demands and numerical instabilities, which make calculations both difficult and time consuming. To address these challenges we develop and test a cheaper-to-run surrogate model, which aims to emulate the response of an original model. The surrogate model is set up by lumping the original model into compartments. These are confined areas in which the volume is modelled by surrogates. We develop two types of surrogates: (i) The drainage system is modelled by response surface surrogates, which are empirical data driven models. These are trained using the volume-discharge relations by piecewise linear functions. (ii) The surface flooding is modelled by lower-fidelity physically based surrogates, which are based on surface depressions and flow paths. A surrogate model is set up for a case study area in Aarhus, Denmark, to replace a MIKE FLOOD model. The drainage surrogates are able to reproduce the MIKE URBAN results for a set of rain inputs. The coupled drainage-surface surrogate model lacks details in the surface description which reduces its overall accuracy. The model shows no instability, hence larger time steps can be applied, which reduces the computational time by more than a factor 1400. In conclusion, surrogate models show great potential for usage in urban water modelling.

KEYWORDS

Emulation, Flood, Hydraulic modelling, Surrogate, Urban drainage

1 INTRODUCTION

Climate change coupled with urbanization is expected to increasingly overburden the urban drainage systems in the future. Hence, if no action is taken there will be an increased risk of pluvial flooding and in the number of combined sewer overflows (Arnbjerg-Nielsen et al. 2015).

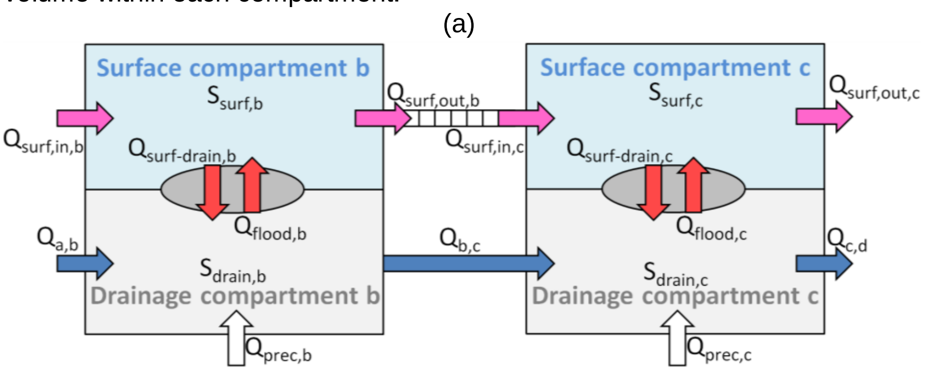
In order to decrease future flood related costs adaptation measures must be implemented. In order to calculate the efficiency of adaptation options the flows within and outside of the drainage system during extreme events must be known. This is typically modelled with high fidelity models such as MIKE URBAN and MIKE FLOOD, which are physically based distributed models. However, due to their large computational requirements their usage is impeded for applications like e.g. real-time usage, uncertainty analysis and optimization (e.g. Wolfs et al. 2013). Furthermore, the models provide very accurate results on an uncertain basis.

Models describing flow routing on surface and in drainage networks are generally divided into two main groups: physically based distributed models, which often apply the Saint-Venant equations, and lumped conceptual models (e.g. Chow 1964). For stormwater management a range of distributed physically based models are available. In this study MIKE by DHI is used (DHI, 2014). MIKE URBAN applies the 1D Saint-Venant equations to describe the flow routing in the drainage system and MIKE 21 applies the 2D Saint-Venant equations for surface routing. These are coupled by the orifice equation in MIKE FLOOD. In this study lumped conceptual models are developed to replace a MIKE FLOOD model to reduce computational requirements. These are surrogate as they serve to emulate the response of the original MIKE FLOOD model. Two different types of surrogates are developed: response surface models and lower-fidelity physically based models. The first type empirically estimates the model response by data-driven function approximations. The second type is physically based but with less details than the original model (Razavi et al. 2012).

2 METHODS

2.1 Model Formulation

The original model is divided into compartments. These are confined areas of the model in which the volume of water is modelled by a surrogate. A single surrogate is a volume based reservoir model, dependent on the water volume in the reservoir itself and the in- and outputs. Surface response surrogates simulate the drainage system and lower-fidelity physically based surrogates simulate surface routing caused by flooding. A conceptual model of two drainage and surface compartments, b and c, can be seen in Figure 1a. The precipitation input is directly inserted in the drainage compartment by the time-area method. Thus the only water on the surface will be due to surcharging. From here the water can move to downstream compartments or surcharge to the surface. In the surface compartment water can enter from the drainage compartment. It can then be discharged to downstream surface compartments through transportation cells or discharge back into the drainage compartment. These in- and outputs are used to create mass balance equations for the changing volume within each compartment.



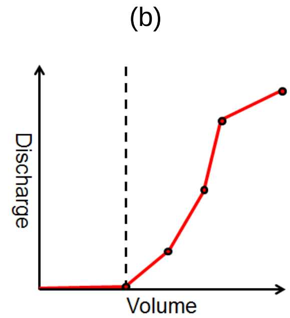


Figure 1: (a) Conceptual drawing of surface and drainage compartments b and c in connection. (b) Sketch of determining volume-discharge relations by approximating steady state points (dots) from MIKE URBAN by linear functions (red lines), threshold for discharge (dashed line).

2.2 Estimation of parameters

To train the drainage surrogates, MIKE URBAN is simulated for a staircase rain covering a range of different intensities. The duration of each step is set to the point where the system has reached steady state. Hereafter, the steady state volumes in the defined compartments and discharges in and out of the compartments are extracted from MIKE URBAN. These steady state points are afterwards connected by piecewise linear functions describing the volume-discharge relation for each compartment as seen in Figure 1b. This is both done for the exchange of water between the drainage compartments and the discharge to the surface. The surface parameters for the surface surrogates are obtained from a GIS analysis. Water is discharged to the transportation cells when the volume of water in the surface compartment exceeds the maximum volume available in the surface depressions. In the transportation cells the water is routed to the downstream compartment with the Manning equation, where Manning's roughness coefficient is set to 32 $m^{1/3}/s$ and the width to 8 m. Water will re-enter the drainage compartment from the surface compartment if the volume of water in the drainage system is below the volume threshold for flooding (indicated by the dashed line in Figure 1b).

3 RESULTS AND DISCUSSION

Figure 2 shows the case study area of Åbyhøj/Hasle, Aarhus in Denmark. Figure 2a shows the drainage system and the compartments. The discharges between the drainage surrogates are determined by training volume-discharge data for each compartment (e.g. Wolfs et al. 2013).

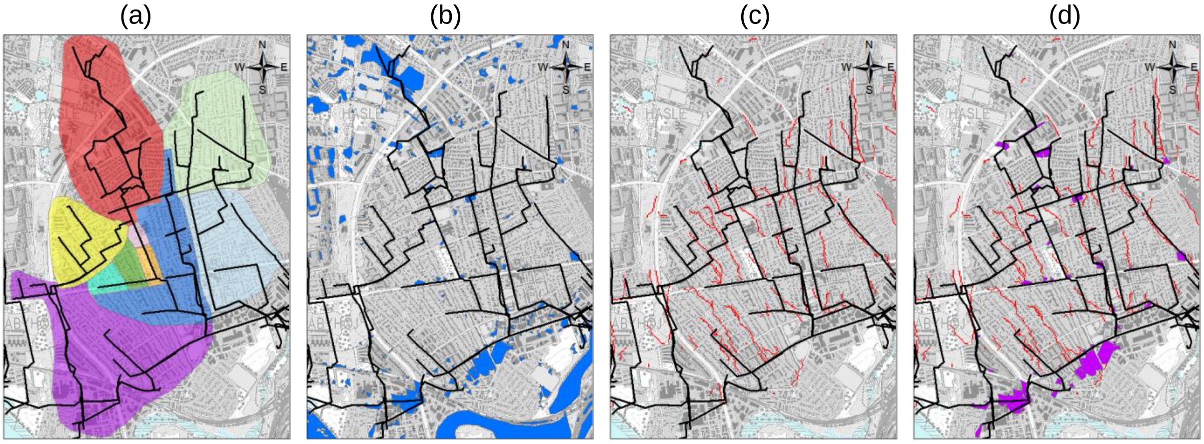


Figure 2: Case study area of Åbyhøj/Hasle in Aarhus Denmark (map size 3.6x2.7 km). (a) Pipes (black lines) and compartment division (coloured areas). (b-d) Process of the GIS analysis for creating the surface compartments. (b) Identification of depressions (blue areas) (c) Identification of flow paths (red lines) (d) Combination of information about depressions and flow paths to select depressions for the analysis (purple areas).

To set up the surface surrogates the following steps are conducted. First a GIS analysis is done to identify all depressions above a certain volumetric threshold. Next the major flow paths are found. Hereafter, depressions located near the drainage system or on a major flow path are selected. Finally the routing between the selected depressions is conducted to set up the model. Figure 2b-d shows steps 1-3 for the case study area.

The surrogate model is tested with a range of different rain events. Figure 3a-d shows the results of the drainage surrogate model compared to a MIKE URBAN model for a block rain with a pulse. Figure 3a-b shows a comparison of the modelled volume and discharges over time for two compartments. The drainage surrogate model has an overall good fit to the MIKE URBAN model with few discrepancies. Figure 3c-d shows the volume-discharge relations computed by MIKE URBAN and the steady state points used to train the surrogates for these two compartments. When volume-discharge relations in MIKE URBAN diverge from the steady state points (Figure 3d), the fit of the surrogate model decreases (Figure 3b). However, even though the MIKE URBAN model does not follow the steady state training data, the surrogate model still captures the magnitude and timing of the peaks. The influence of hysteresis and dynamic effects are of less importance for this case study and steady state data can thus be applied. For more flat catchments with looped networks with reversed flows and effects such as backwatering, the model should be expanded to include these effects.

Figure 3e shows the resulting maximum water levels in the selected depressions for the surrogate model and MIKE FLOOD model for two compartments. The fit of the surrogate model is varying. Some selected depressions are wrongfully included/disregarded, which affects the accuracy of the surrogate model (see Figure 3e top). However, when the correct depressions and connections are included the magnitude and timing is accurate. The surface results are thus promising but highly dependent on the process of identifying the surface system (Figure 2b-d), which involves decision making from the modeller. As the flows between the depressions are modelled as a simple plug-flow transport, backwater effects are not included. For more flat areas where these effects could occur, the model should therefore be expanded to include this.

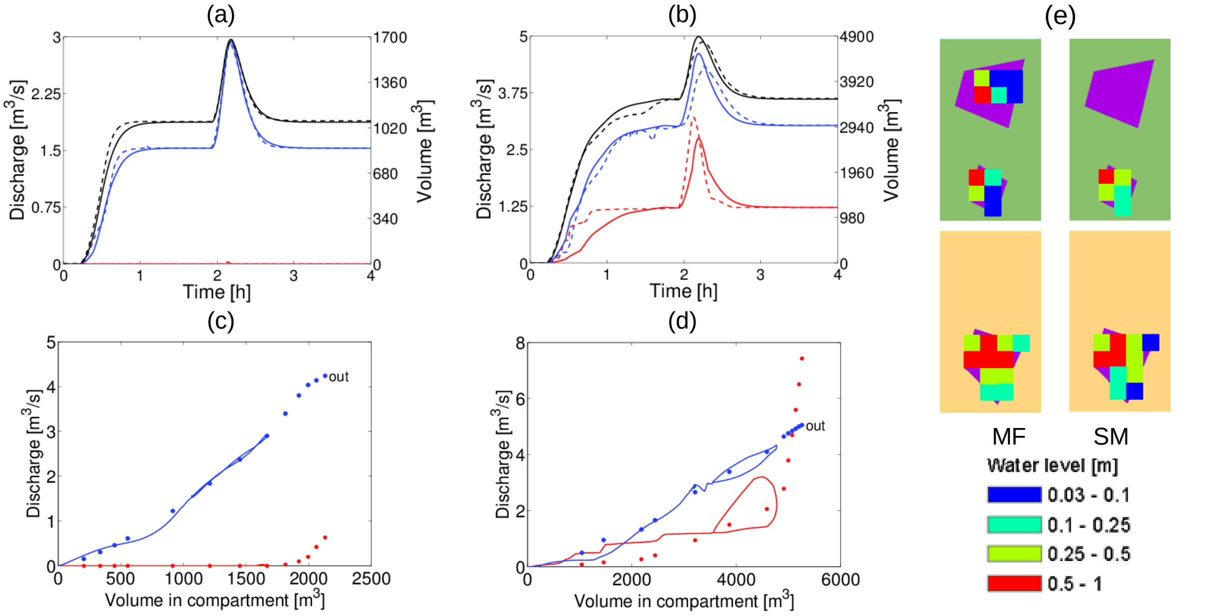


Figure 3: (a-b) Surrogate model (solid lines) resulting volumes (black) and discharges (flood red, drainage blue) compared to results from MIKE URBAN (dashed lines). (c-d) MIKE URBAN volume-discharge curves with training steady state points. (e) Surrogate model (SM) and MIKE FLOOD (MF) resulting maximum water levels in selected depressions for two compartments (background colours indicates compartment location in Figure 2a).

The surrogate model does not show any instability, which allow for larger time steps than MIKE FLOOD. The time steps can thus be chosen based on the temporal resolution of the rain input and the purpose of the simulation. When applying a time step of 10 min the surrogate model is 1400 times faster than the MIKE FLOOD model. An additional order of magnitude of at least 10 times more efficient is expected when optimizing the code and shifting programming language. This is currently being examined.

4 CONCLUSION AND OUTLOOK

This study addresses the computational challenges of flood modelling in urban areas by replacing a MIKE FLOOD model with a surrogate model. The drainage surrogates show good results, but the method needs to be further developed to include reversed flows and backwater effects. The surface results differ for some compartments due to errors in the model set up, but show overall to be promising. The stability and reduced computational time of the surrogate models indicate that there is great potential for further use of surrogate models in urban flood modelling.

AKNOWLEDGEMENT

The effort of Morten Borup and Jens Toke was partially supported by the Smart Cities Water Solutions project, which is funded by Realdania under the Klimaspring programme.

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