

Challenges of Urban Hydrology in Modelling Extreme Rainfalls

Les défis de l'hydrologie urbaine dans la modélisation des pluies extrêmes

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RÉSUMÉ

L'utilisation de la technologie des modèles de simulation pour les études de ruissellement pluvial est considérée comme une méthode standard dans la société numérique moderne. Cependant, tous les modèles de simulation sont soumis à de nombreuses incertitudes liées à la complexité de l'environnement à modéliser. Les résultats des modèles sont biaisés et ne fournissent pas les informations précises nécessaires pour un investissement optimal à long terme dans les infrastructures hydrauliques. Le défi majeur pour les spécialistes de la modélisation urbaine est de réduire le niveau d'incertitude associé aux différentes phases de la modélisation. L'article se concentre sur les incertitudes liées à la modélisation hydrologique du ruissellement pluvial dans le réseau de drainage. La méthode de modélisation dite « Temps-Surface » (basée sur les polygones de Thiessen), fréquemment utilisée dans le domaine du génie urbain, est jugée produire des résultats sous-estimés, en particulier pour des pluies de forte intensité et de longue durée. Les auteurs visent à quantifier cette incertitude et proposent une méthode alternative (TAMod) afin de réduire le biais hydrologique dans les résultats de modélisation.

ABSTRACT

Use of simulation model technology for stormwater runoff projects is considered as standard approach in civil engineering practice. However, simulation models are subjected to many uncertainties associated with the complex environment to be modelled. Model results are biased and do not provide accurate information necessary for optimal long-term investment into water infrastructure. It is challenge for urban modelling specialists to reduce the level of uncertainty associated with distinct modelled processes. The paper focusses on uncertainties associated with hydrological modelling of stormwater runoff into drainage network. Frequently used in urban engineering domain "Time-Area" modelling method (based on Thiessen polygons) is argued to provide underestimated results especially for heavy rainfalls with high intensities. Authors aim on quantification of this uncertainty and suggest alternative method (TAMod) to improve level of surface runoff modelling results.

KEYWORDS

Climate Change, Extreme rainfall, Runoff Modelling, Urban hydrology

1 INTRODUCTION

Simulation of hydrological processes in urbanized areas has become a standard engineering approach in western countries over last 30 years. In Europe, the Rational Method based surface runoff modelling is widely used as successor of rational method design approach. This method considers urban runoff as excess of precipitation from impervious areas after initial losses are filled up. Such approach is correct and applicable for simulation runs where rainfall intensities and precipitation sums stay in range of rainfall events used for calibration. However, once the size of rainfall used for design or assessment exceeds calibration values, the simulation results start gradually deviating from reality.

Increasing frequency of extreme heavy rainfalls associated with Climate Change demands incorporation of extreme rainfall modelling into engineering practice. Under these conditions current modelling approach cannot be efficiently applied as whole area of urban catchment gradually starts producing runoff (including areas such as parks or gardens). The assumption of fixed constant value of impermeable area contributing to the urban runoff is not valid any longer for extreme rainfalls. The alternative approach to surface runoff is to be applied.

1.1 Limitations of hydrological methods used in urban drainage domain

There are distinct methods used to simulate urban hydrology processes based on distinct level of simplification and modelling analogy applied. In Czech Republic, rational method based approaches are dominant by making use of total impervious areas, initial losses and time of concentration parameters defined on Thiessen polygon based sub-catchments (Figure 1). Such approach is implemented for instance in the simulation model MIKE URBAN (©DHIGroup) in a form of “Time-Area” method.

Surface runoff model requires calibration e.i. appropriate values of surface runoff parameters are to be defined for modelled urban catchments based on monitoring data. Final runoff model is produced at the end of model calibration and as such it is further used for distinct planning or assessment purposes. This means that all calibrated hydrological parameters stay untouched as internal “constants” of surface runoff model for further modelling works. Presented approach however incorporates danger for heavy and extreme rainfall modelling as obviously only small and medium size rainfall is recorded during monitoring campaigns (lasting only for few months). In consequence, calibrated model parameters can more or less deviate from reality.

As known from nature, distinct surfaces generate distinct runoff based on surface type, initial infiltration conditions and based on catchment morphology. The surface runoff is produced primarily by impervious areas (roofs, streets, etc.) under ordinary meteorological conditions. However, during heavy and extreme precipitation events situation changes. Runoff starts gradually contributing not only from impervious surfaces but also from semi pervious surfaces and finally also from permeable surfaces such as parks or gardens. For such events the assumption of “constant” (calibrated) value of impermeable surface does not hold as ultimately full surface of urban catchment can start producing runoff. There is a question what alternative approach can be used to minimize this type of uncertainties incorporated in simulation model.

2 APPROACH TO EXTREME RAINFALL SURFACE RUNOFF MODELLING

“Time-Area” method frequently used method for simulating urban surface runoff in European cities makes use of Thiessen polygons defining total contributing area for specific pipe section. This approach originates from historical period when lack of catchment data was substituted by generic catchment information such as total size and runoff coefficient. At present, distinct catchment data are available in digital form such as orthophotos, property cadaster, catchment morphology contour lines, soil type maps, point clouds, etc. These remote sensing data act as game-changer for surface runoff modelling. The authors made use of all available catchment information to adapt currently used “Time-Area” (TA) method into the form suiting better for simulating extreme rainfall events as argued about in previous paragraphs.

New alternative surface runoff method was invented on basis of original TA method as this method is commonly used in Czech Republic and prevailing number of urban drainage simulation models make use of this method. The intention was to modify this method for incorporating current digital surface data. The modified “Time-Area” method (TAMod) was introduced by replacing original Thiessen polygons with real polygons (sub-catchments) representing distinct catchment categories such as roofs, roads, gravel, sand, grass, forest, etc. (Figure 1).



Figure 1. Surface hydrology used in TA (left) and in TAMod (right) method

The runoff from these “categorized” sub-catchments is then primarily triggered by value of initial loss applied for whole polygon area. Such way, the catchment surface properties are more accurately described to reduce the surface modelling uncertainty while allowing for simulation of heavy and extreme rainfall events as all sub-catchments are contributing to the runoff based on initial loss value. This approach then resolves original constrains of “constant value” of imperious areas set up during calibration process using original TA method.

2.1 Study case „Bechovice“

Presented approach was implemented and tested on pilot project located in urban district of Bechovice at the outskirts of the city of Prague (Figure 2). 1D urban drainage simulation model was developed and calibrated for this locality. Standard “Time-Area” surface runoff model was primarily used for modelling of surface runoff in this model. The simulation model was then updated based on alternative TAMod surface runoff method. Land registry (cadaster), land use map, soil map and vegetation index map were used as source data to define distinct types of surfaces such as roofs, asphalt or concrete roads and parking, pavement sidewalk, gravel, grass and gardens. These “categorized surfaces” were then directly connected to the relevant manhole inlets similarly to Thiessen polygon catchments used in original TA runoff method. Final comparison of surface details is presented for both original TA and alternative TAMod models in the following figure (Figure 2). The locations “1” and “2” indicated in red on both figures represent two locations where TA and TAMod methods were compared.



Figure 2. Complexity of surface runoff model TA on Bechovice study case area

The alternative TAMod model and TA model were calibrated on same monitoring data set. Initial loss parameter was primarily used for TAMod calibration (roof-0,6mm, asphalt-10mm, concrete-15mm, pavement-18mm, gravel-20mm,grass-25mm). Calibration results and match between TA and TAMod models are presented for location point MP01 on next figure. Each calibration graph is composed of original monitoring discharge data (in black), calibrated runoff data based on TA model (in blue) and calibrated TAMod model (in red). The calibration results were quantified for both TA and TAMod methods using set of objective functions making sure TAMod to provide similar fit as presented for original TA surface runoff method.

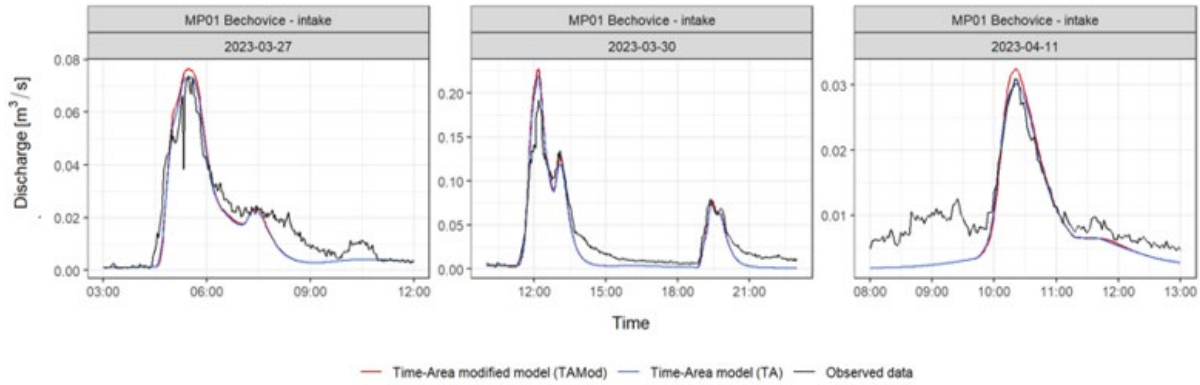


Figure 3. Monitoring discharge (black) and calibration results for TA (blue) and TAMod model (red)

2.2 Discussion of Results

Both TA and TAMod runoff models were tested on selected extreme precipitation events. IDF based 30 minutes block rainfalls with return periods of 1, 2, 5, 10, 50 and 100 years were selected for performance assessment. The results of the model performance for both methods are presented below for selected model location 1 (MP01). TA model results are represented in blue color while TAMod results in red color. Figure shows the flow hydrograms (left), total flow volume (middle) and peak flow (right) for all six simulated rainfall events.

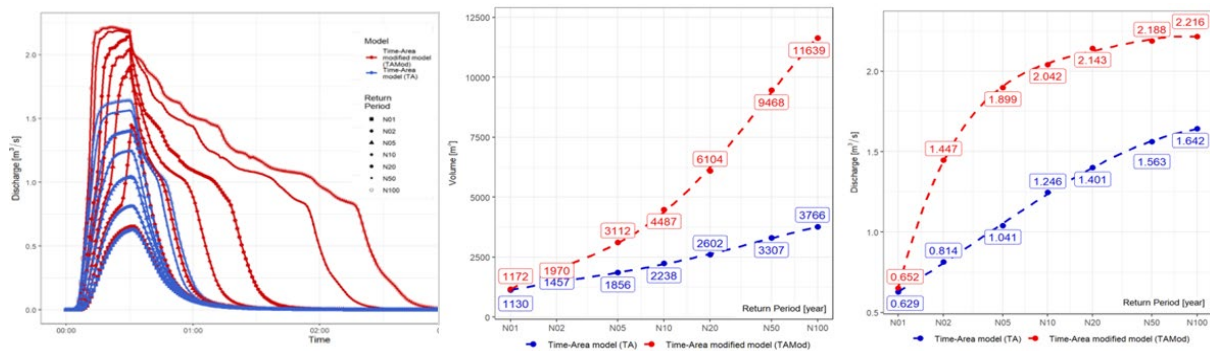


Figure 4. Result comparison between TA (blue) and TAMod (red) model results for N01-N100 rainfalls and MP01 profile

The simulated results confirm the importance of modelling runoff from all contributing surface types. As shown on the figure, deviation between TA and TAMod results increases with increased extremity of rainfall. For modelled locality classical TA model can be successfully used up to 1 year return period rainfall while for higher intensity rainfalls this model starts underestimating surface runoff from semi-pervious and pervious surfaces. Difference in results for TA and TAMod runoff model (Figure 4) indicates level of uncertainty (underestimation) inherited in TA model in consequence of increasing size of rainfall.

3 CONCLUSIONS

Ongoing climate change is being gradually recognized in Czech Republic. Extreme precipitation events (such as cloudbursts) are understood as one of the most visible impacts of this change in our region (in parallel with heat waves and droughts). It seems clear that our society needs to adapt it's structure and functions to survive the future. In terms of urban drainage domain, new design and construction methods and new requirements for long term performance of urban water infrastructure are needed. This demand applies also for urban drainage simulation models currently used as standard design and assessment means in urban water practice.

In the paper authors discussed uncertainties associated with simulation of extreme precipitation events using one dimensional simulation models. As argued, currently used models underestimate value of urban runoff for heavy and extreme rainfalls due to gaps in description of surface runoff processes. The level of model deviation from reality increases with increasing extremity of rainfall. These findings are considered as bottleneck for design

and assessment projects or studies where extreme rainfall simulation is required. Results of modelling works provide not adequate information in terms of network capacity, surcharge and volumes e.i. diverted from combined sewer overflow CSO or necessary retention basin volumes. This way needs for network reconstructions or for planning of future drainage system development is underestimated.

Authors identified sources of uncertainties implemented in current surface runoff simulation models (TA "Time-Area" rational method mostly used in Czechia). The alternative rainfall runoff method TAMod was introduced aiming to help resolving current challenge in simulation of extreme rainfalls. This method makes use of detailed surface information to reduce level of uncertainties in surface runoff modelling by providing runoff from all types of urban surfaces.

The alternative rainfall runoff method (TAMod) was developed and tested on several project cases. This method is capable to effectively substitute current rainfall runoff methods (such as "Time-Area") by profiting from more realistic simulation of full spectrum of rainfalls. TAMod method helps supporting need for accurate runoff models capable to simulate Climate Change induced extreme rainfalls.