WetSpa-Urban: the comprehensive tool for runoff calculation in an urban areas

L’outil complet pour le calcul du ruissellement en zone urbaine

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RÉSUMÉ

En raison de l'urbanisation rapide des dernières décennies, près de 55 % de la population mondiale vit maintenant dans des zones urbaines (Nations Unies). En raison de la complexité croissante de la géométrie du terrain, des modèles plus détaillés sont nécessaires pour une estimation précise du ruissellement. Au cours des 20 dernières années, de nombreux outils de modélisation ont été développés, chacun avec ses avantages et ses inconvénients. Afin d'éviter de perdre du temps, de l'argent et des efforts dans le développement de nouveaux logiciels, un outil appelé WetSpa-Urban a été développé qui consiste à relier le modèle de bassin versant WetSpa au modèle de drainage urbain SWMM. Comme WetSpa (Liu et De Smedt, 2004a) est un modèle entièrement distribué basé sur un SIG, il représente avec précision les processus hydrologiques pour le calcul du ruissellement de surface. De plus, SWMM (Rossman, 2010) est un logiciel hydrodynamique capable de calculer avec précision les processus d'écoulement des conduites. La fusion de ces outils et certaines modifications, telles que l'accélération du calcul du ruissellement de surface et la simulation de l'écoulement au niveau des sous-bassins versants, font du WetSpa-Urban un outil complet de ruissellement pluviométrique adapté aux études urbaines. Cette étude a été réalisée dans le bassin versant de Watermaelbeek dans la région de Bruxelles, en Belgique. Après l'accélération des processus, la performance du calcul du ruissellement de surface a augmenté de près de 130 %. En évaluant le débit simulé par rapport au débit observé à la sortie du bassin versant pour 2015, l'efficacité de Nash-Sutcliffe a atteint 88 % et 85 % pour les périodes d'étalonnage et de validation, respectivement. Ceci est significativement plus élevé que le NSE de 75% obtenu avec le WetSpa original fait par Wirion (2017).

ABSTRACT

Due to rapid urbanization in recent decades, almost 55 percent of the world’s population are now living in urban areas (United Nations). As a result of increasingly complex land geometry, more detailed models are needed for a precise estimation of runoff. In the last 20 years, many modeling tools have been developed; each with its pros and cons. In order to avoid spending time, money and effort on developing new software, a tool called WetSpa-Urban was developed that consists of the linking of the catchment model WetSpa to the urban drainage model SWMM. As WetSpa (Liu and De Smedt, 2004a) is a fully distributed GIS-based model, it is accurately representing hydrological processes for calculation of surface runoff. In addition, SWMM (Rossman, 2010) is a hydrodynamic software capable of calculating pipe flow processes accurately. Merging these tools and making some modifications, such as speeding up surface runoff calculation and simulating flow at the sub-catchment level, makes the WetSpa-Urban a comprehensive rainfall-runoff tool suitable for urban studies. This study was carried out in the Watermaelbeek catchment in the Brussels region, Belgium. After the speeding up processes, the performance of surface runoff calculation increased by almost 130%. By evaluating simulated flow versus observed flow at the outlet of the catchment for 2015, the Nash–Sutcliffe efficiency reached to 88% and 85% for the calibration and validation periods, respectively. This is significantly higher than the NSE of 75% that was obtained with the original WetSpa done by Wirion (2017).

KEYWORDS

(GIS, hydrodynamic, rainfall-runoff, software, urbanization)

1 INTRODUCTION

The most recent study done by (UN Population Division, 2018) estimated that more than 55 percent of the world's population was living in urban areas in 2018. Rapid urbanisation has a significant impact on urban runoff, with the natural environment being replaced by impervious materials including concrete, asphalt, etc. Sealing the urban surface increases the heterogeneity and complexity of land and has resulted in dramatic changes to soil type and slope. As a result of these transformations, the quality and quantity of stormwater runoff are prone to change.

In order to understand the hydrologic behaviour of urban areas and tackle urban problems such as flood and combined sewer overflow (CSO), a reliable rainfall-runoff model is needed. Singh and Woolhiser (2002) found out that the first generation of rainfall-runoff models goes back to the 19^{th} century with developments by Imbeau (1892). The current versions capable of simulating runoff quality and quantity are based on works done using the models developed by the US governmental agencies in 1970 (Zoppou, 2001). Nowadays, several urban runoff modelling tools have been developed by different organisations, and the development of new/adapted/improved models will most likely never stop. Singh and Woolhiser (2002) made a list of more than 70 rainfall-runoff models for different types of watershed, each with unique pros and cons.

The level of detail in the representation of over and the underground processes in urban catchment models varies. They also vary in the representation of spatial and temporal resolution. Due to the short response time of the urban catchment and flash floods, scientists tend to use high-resolution products such as MOUSE (2003), SWMM (Rossman, 2010) and WetSpa (Liu and De Smedt, 2004a). Although MOUSE and SWMM are suitable and well-known flow simulation tools in small-scale catchments, only SWMM is freely available for users (Elliott and Trowsdale, 2007a). Such free availability of software is a crucial point for specific users to decide whether they can use it for their projects or not.

In today’s world, due to the improvement in computer science and land mapping, newly developed softwares tend to use geographic information systems (GIS) and remote sensing data in their fully distributed surface runoff calculation. WetSpa (Liu and De Smedt, 2004a) is an excellent example of this. The importance of using remote sensing and GIS data becomes prominent when simulating flow in urban lands. In using these data, instead of average slope in each sub-catchment, the slope of every single pixel can be considered at high resolution for calculation of surface runoff. This is a very import accomplishment for urban planners because it allows further implement different practices of low impact development (LID) in order to improve social and environmental aspects of urban lands (Elliott and Trowsdale, 2007b).

Due to the sheer number of stormwater flow software programs available for urban catchment modelling, it would be practical for scientists could stop developing new modelling tools and use the strength of available softwares. The primary objective of this research is developing a new tool called WetSpa-Urban by coupling the surface runoff section of WetSpa (Liu and De Smedt, 2004a) together with underground processes calculated by SWMM (Rossman, 2010). This is the best methodology to overcome the shortcoming of both individual models and generate a compelling and functional surface runoff software suitable for urban catchments. The Watermaelbeek sub-catchment situated in upper Woluwe catchment in Brussels region is studied in this research to check the applicability of the WetSpa-Urban software. The study area is around 6 km^2 with an average rainfall of $780 mm \cdot year^{-1}$.

2 METHODOLOGY

The new modelling tool WetSpa-SWMM coupled two different softwares, WetSpa developed by Vrije Universiteit Brussel (VUB) and SWMM developed by U.S. Environmental Protection Agency (EPA). The WetSpa-Python version (Salvadore, 2015) is used for surface runoff calculation. This is a GIS-based fully distributed physical rainfall-runoff model which has no limits regarding simulation time step that makes it suitable for urban areas. By considering the geomorphological characteristic of each pixel, runoff is calculated by applying a method called modified coefficient. Then, the runoff water is routed with use of Instantaneous Unit Hydrograph or IUH (Liu and De Smedt, 2004b) together with linear diffusive wave approximation (Miller and Cunge, 1975). Since this software was not explicitly designed for urban applications, there is no module to route the surface runoff through a sewer network towards the outlet of a catchment. To this purpose, a coupling with SWMM is realised in order to calculate the flow in hydraulic structures. This is achieved by the Barré de Saint Venant equations to calculate flow and depth in each pipe (Rossman, 2010).

As the original WetSpa was used for the calculation of overland flow at the catchment scale, there is a need to modify the model in order to calculate the flow at sub-catchment level. This is mainly because of the complex geometry of urban landscapes that it is necessary to calculate runoff at a smaller scale and route it through the sewer network in order to approximate better the reality. In this new concept, the sub-catchments are defined by considering both the flow accumulation map generated based on the Digital Elevation Model (DEM) combined with the division of drainage zones determined by the position of pipes and nodes. In other words, the sub-catchment division is not restricted to the slope of land but also considers the slope of the sewer network, even if it is not following the surface elevation and slope. This allows the runoff generated by areas following the opposite direction of pipes to be redirected to the correct manholes.

An additional constraint of the original WetSpa is its slow calculation time. This is mainly due to the use of high-resolution remote sensing and GIS data (2 m). To make the new software more user-friendly and applicable to use for long-term simulation, the model was sped up using three different methods. First, the programming technique called multi-threading was applied using Python. Using the Psutil (process and system utilities) module allows parallel calculation of the surface runoff for a specific number of sub-catchments simultaneously. Secondly, optimisation of the codes (simplifying and rewriting the equations by defining some constants to avoid repeated calculation) increased model performance. Finally, a reduction of calculation time is obtained by imposing a reduction of the maximum length of the IUH (maximum time of concentration) by limiting mean travel time to the catchment outlet (t0_h). This causes that a less complex matrix has to be solved for the calculation of runoff.

After modification and coupling of the original tools, the WetSpa-Urban simulates the flow at the outlet of catchment in three different steps. First, meteorological data such as rainfall and evapotranspiration together with high-resolution land-use, soil and elevation map in the asci format are provided. These maps are divided into smaller segments by overlaying with the watershed division map. Then, these maps are used as inputs for the pre-processing section of the software. In this part, 26 necessary input parameter maps were automatically derived to produce the runoff coefficient and depression storage capacity map for each sub-catchment (Salvadore, 2015). In the next step, eight global parameters needed to be defined for simulating stormwater from each sub-catchment. These parameters are later modified by calibration for having a better result. Lastly, the surface flow is routed towards the sewer network by assigning the discharge from each sub-catchment to a specific inlet manhole.

3 RESULTS AND DISCUSSION

By combining the DEM and watershed division maps provided by the VIVAQUA a new watershed map containing 38 sub-catchments was generated. Later, the discharge from some of the sub-catchments was combined due to the limitation of having detailed sewer network (all inlet nodes) and redirection of flow to the correct inlet manholes (32).

Although python is slower than other programming languages like C++, by simplification and rewriting equations and some codes the model running time is 30% faster. As explained above, the parameter called "maxt" (maximum time of concentration) in WetSpa has a direct relation with the number of IUH. In this case, maxt varies between 2 and 11 for different sub-catchments, but 4 and 5 are the most dominant values. By reassigning the value of pixels with unrealistically high "t0_h" (mean travel time to catchment outlet) to a certain level, smaller IUH is achieved for sub-catchments with high maxt. As an example, by only reassigning the "t0_h" of less than 1% of pixels in sub-catchment 15, the maxt reduced from 6 to 3. This method would be a great help, as the uncertainty added to the simulation through keeping the original elevation map and only doing the modification in IUH calculation is not that high when compared with the considerable improvement in model performance. In general, the average maxt reduced from 5 to 3.7 by only changing less than 1% of pixels value for t0_h in 13 sub-catchments. The multithreading approach used in WetSpa-Urban makes the model almost two times faster compared to original WetSpa. For instance, the time needed for calculation of surface runoff for one time step reduced from 10 sec to 4.2 sec in sub-catchment 30. The 10-minute precipitation and evapotranspiration data for two different periods (January-February and July-August) in 2015 are used for calibration. These two periods are selected for calibration as mainly the second period (summer) is characterised by high rainfall intensity during convective storms in, while and the least number of dry period together with high average rainfall intensity in the first selected period. The simulation results are evaluated by Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970). The NSE of 88% is reached for the calibration period which is a satisfactory result. The flow simulation versus observation for a selected period in January 2015 can be seen in Figure 2.

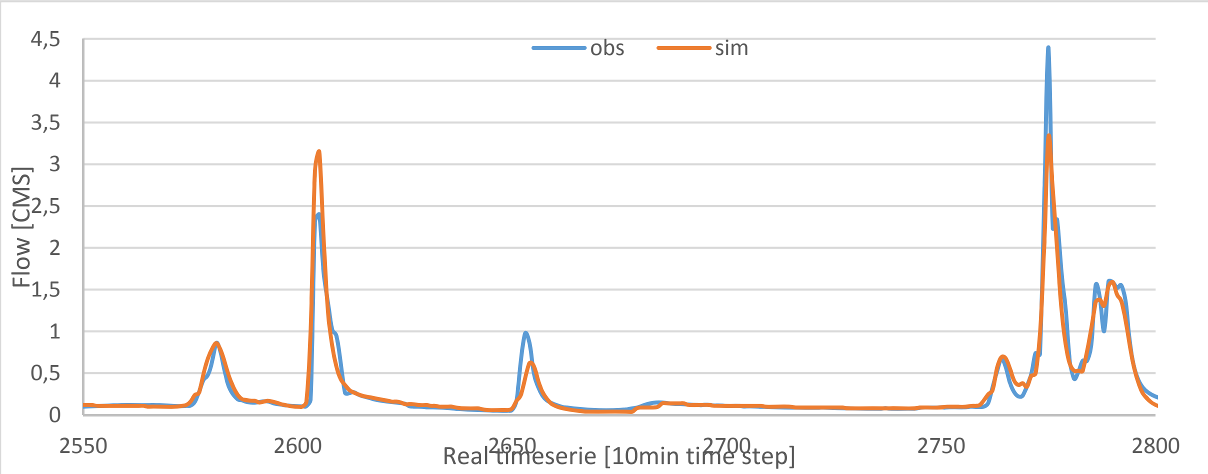

Figure 1: Simulated runoff by WetSpa-Urban versus observation at the outlet of Watermaelbeek catchment

The low flow, especially dry weather flow (DWF) was simulated well, but for the peaks with high flow, some overestimations and underestimations are observed. It is also worth mentioning that the timing of most simulated peaks is very well fitting to the observations. Also, NSE for the validation period (all months excluding the calibration period in 2015) reached 85%.

4 CONCLUSION

Compared to the research done by Wirion (2017) for the same catchment with original WetSpa, a significant improvement in the prediction of flow is observed (NSE=70 %). This confirms that WetSpa-Urban provides a more realistic representation of the hydrological processes of urban areas. Besides, faster calculation time and having General User Interface (GUI) are the other added value of the newly developed software adapted for urban areas.

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