

# INTEGRATED STORMWATER ANALYSIS MODEL TO SUPPORT SUSTAINABLE URBAN GREEN SPACE DESIGN

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### ABSTRACT:

Urban Green Space (UGS) has been broadly treated as a valuable and limited resource to handle the challenges brought by high-density urban environment. Green stormwater management has been prompt around the world. To reduce the potential conflicts between stormwater management and other requirements on UGS (especially human needs), the research community and governments encourage the urban planners and designers to integrate stormwater analysis into UGS design. However, the professional term and operation of the traditional hydrological model is a huge challenge to the designers who haven't touched hydrological knowledge. This study developed a method to simulate and quantify stormwater in UGS by the particle system in the design platform- Rhinoceros +Grasshopper. In this method, we adopted five groups of urban objects such as terrain, building footprint etc. to ease procedures and performance. To overcome the issue the abstracted particle movement cannot reflect the infiltration features of land cover, we introduced categorising locations of the particles and the UGS retaining stormwater hypothesis. To test the feasibility of the method, we tested the three parameters of the integrated model: iteration times, rainfall depth (selected rainfall event) and particle radius. The comparison tests prove: (1) too small iteration times would lead the particles to stop on the way to the bottom of the terrain, so we set at least 4000 iteration times for simulation; (2) the sensitivity to the selection of rainfall event and particle size is relatively low, the simulation results vary by 1%; (3) too small particle numbers will impact the accuracy of analysis, so we should balance accuracy and work efficiency of work; (4) the stormwater volume estimation based on the particle system is acceptable. The experiments confirm the method can effectively support preliminary UGS design work.

## 1. INTRODUCTION

Sustainable Urban Green Space (UGS) Design is a main trend around the world, which requires considering environmental and social challenges (McPherson, 1992). To support the interdisciplinary design for UGS, the integrated stormwater analysis model has been proposed by the research community. They believe this model more understandable compared to the hydrology model, and helps to reduce the communication effort between different professionals. As a result, the overall negative impact on environment and society from inappropriate UGS design is also minimised (Kuller et al., 2019, Morschek et al., 2019, Chen et al., 2016).

The integrated model can be categorised into two types. One type is still developed based on the professional hydrology model, such as Spatial Suitability ANalysis TOol (SSANTO) rooted in Model for Urban Stormwater Improvement Conceptualisation (MUSIC) and Urban Biophysical Environments and Technologies Simulator (UrbanBEATS) (Kuller et al., 2019); the other type is developed within the 3D spatial design model directly. An example of such models is Spatial Resilience Toolbox – Flooding (SRTF) developed by abstracting stormwater into particles to simulate water flow movement (Morschek et al., 2019). Due to the background of the professional hydrology model, the first one still needs a big bunch of hydrology data as input and complex operations (Kuller et al., 2019, Zhang et al., 2020). Thus, it can provide solid stormwater analysis results to support UGS design, although, it poses a big challenge to urban planners and designers without solid hydrology knowledge to operate it. To the urban planners, designers and developers, the second one integrated within UGS design model would be more friendly to work with. However, up to now, the second type

of integrated model still cannot work independently to support UGS design because it mainly provides water flow visualisation without quantitative analysis result for treating stormwater on-site (Morschek et al., 2019, LUO et al., 2020). Clarifying the volume of stormwater on site is the key basis for green stormwater treatment facility design. Therefore, this paper presents an integrated method to support quantitative stormwater evaluation. The paper intends to:

- (1) Find out a quantitative method of evaluating stormwater integrated in a 3D spatial model;
- (2) Prove feasibility of the integrated quantitative stormwater evaluation.

## 2. EXISTING INTEGRATED METHODS

### 2.1 Particle System

To deal with challenges of hydraulic model (i.e SWMM, MUSIC, UrbanBEATS etc.), urban planners, designers and research groups have been trying to integrate stormwater analysis in 3D design model with particle system method (LUO et al., 2020, Chen et al., 2016). The feasibility of the method for analyzing space features has been broadly tested by various application, such as indoor navigation (Girard et al., 2011), human behavior analysis (Thieu and Melnik, 2021), runoff simulation (Chen et al., 2016, LUO et al., 2020).

The basic logic of particle system method is abstracting stormwater into a set of particles (also called spheres or nodes) to estimate the influence of site environment (i.e. topographic variation) on the runoff movement (Senatore and Piker, 2015). It is widely acknowledged that, following the basic physics law, water flows from the higher level to the lower level, without the influence of an external force. Thus gradient analysis has

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been broadly adopted to simulate the runoff direction in Geographic information systems, such as D8 algorithm (Brun and Band, 2000, Jiang et al., 2013).

The algorithm treats the terrain as a set of tiles and estimates the runoff direction by identifying the slope of each tile with surroundings (Jiang et al., 2013, Wang et al., 2011). In the 3D modelling software - Rhino+Grasshopper - the gradient analysis method is also adopted to estimate the inundation area by iteratively computing the vector pointing 'downhill' direction of sampling terrain tile where the particle is located (see Figure 1(a)). This functionality is available in some plug-ins of Grasshopper such as Grasshopper- Groundhog (Belesky, 2021, Chen et al., 2016). Physics Engine is employed to simulate the particle movement as well. For example, Kangaroo, an interactive physical simulation engine within Grasshopper, has been used to simulate runoff in some research work (Morschek et al., 2019).

The logic of the engine simulation is based on the vector pointing from the particle location towards lower area of surroundings. The difference between the Physics Engine and the Gradient analysis is that the engine includes gravity loading into computation. The engine calculates the rolling down distance of a particle with a certain mass at a unit time by the velocity generated by gravity (see Figure 1(b)). Therefore, compared to the simulation result of Gradient analysis, the final stop spot of the particle is similar, but the decay of the particle velocity is a process and the particle in Physics Engine simulation will pass the bottom point of terrain and continue running for a while before stop at the bottom. In addition, the segment lengths of the particle movement path within the Physics Engine simulation result vary based on the terrain slope of the particle location, rather than keep it similar. At the steeper area, the path segment will be longer.

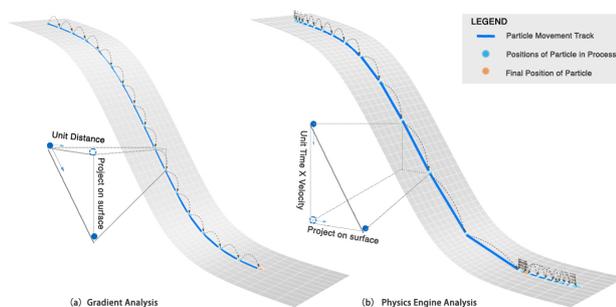


Figure 1. Comparison of Gradient Analysis and Physics Engine simulation result

However, no matter Gradient Analysis or Physics Engine is applied with the particle system, there are three common parameters impacting the analysis result:

- (1) iteration times: if iteration times is set small, the particle will stop at the process of rolling towards the lowest point of terrain ;
- (2) depth of rainfall (rainfall event): if the rainfall depth is set small, the particle amount would be small as well. Then, the particle system cannot be sensitive to every variation of the topography because the particles within the system cannot cover all tiles of topography;
- (3) particle size: if the total volume of particles represents the same stormwater volume, over large size of a single particle will impact the total number of particles and further impact the accuracy of the simulation.

## 2.2 Existing Integrated Methods

Currently, the application of the particle system method in integrated stormwater management design has been broadly accepted (Chen et al., 2016, Weaver, 2019, Charalampidis and Tsalikidis, 2015). One of these integrated methods' working platforms is Rhinoceros 3D + Grasshopper which is an interactive parametric analysis and design environment (Belesky, 2018). To support the primary design work, the integrated methods need to provide the volume of stormwater for treatment and the inundation area estimation. As mentioned above, the existing integrated methods can be divided into two categories. One type is still relying on professional hydrological analysis for quantitative volume evaluation (i.e. Rainwater +) (Chen et al., 2016), the other one is directly linking quantitative evaluation to the particle system (i.e. Spatial Resilience Toolbox - Flooding) (Morschek et al., 2019).

### 2.2.1 Methods Working With Hydrological Analysis

Rainwater + is one of the representatives for the integrated analysis methods adopting professional hydrological analysis. It is developed by Chen et al. (2015) to facilitate sustainable urban stormwater management design. Within Rainwater +, the stormwater analysis includes two parts of computation. The first part adopted the professional hydrological method - the Natural Resource Conservation Service (NRCS) Curve Number method to estimate the volume of stormwater would treat in UGS (Chen et al., 2016). This part still requires the urban planners and designers to deal with hydrological data input and analysis, such as estimating runoff depth based on the soil infiltration features. This particle system method is only adopted to identify the runoff direction and the inundation area based on gradient analysis.

There is similar research. For example, Weaver (2019) worked with Modified Rational Method (MRM), Federal Aviation Administration (FAA) Method and NRCS to estimate runoff quantity (Weaver, 2019). In this approach, the researchers didn't list out the amount of the particles and the iteration times they set. In this way, they avoided the challenge of quantitative evaluation with the particle system. Yet, it does not sufficiently fix the difficulty of designers operating the hydrological models.

### 2.2.2 Methods Evaluating Stormwater With Particle System

Luo et al. (2020) set 5000, 10000 and 30000 particles to simulate light rain, moderate rain, and heavy rain with Gradient Analysis separately (LUO et al., 2020). Although this study didn't clarify the diameter or volume of the particle, it linked the particle number changes to different levels of rain. Similarly, Spatial Resilience Toolbox - Flooding (SRTF), an integrated tool for flooding risk evaluation, translates the total runoff volume into a set of particles and compares the number of particles gathered at the inundation areas to identify the risk level of each inundation area (Morschek et al., 2019). This study intentionally defined a certain amount of particles (10000) with the same radius (30 centimetres) to simulate a rainfall event with 4 litres of stormwater per square meter (Morschek et al., 2019). Yet, it didn't calculate the exact volume of stormwater, so it still cannot provide support for scale estimation of the stormwater facility design.

These studies demonstrate that the research community has realised, following the Law of Conservation of Matter, that particle systems can be used for quantitative stormwater evaluation. However, except for the inundated risk level, the existing studies still cannot provide the way for exact runoff quantity evaluation. Although SRTF has defined a rainfall event with 10000 particles, it didn't explain how to set the particle amount to adapt to different geographical environments. Meanwhile, the volume estimation should consider not only the gradient features but also the infiltration features of the different land cover on site. Grill

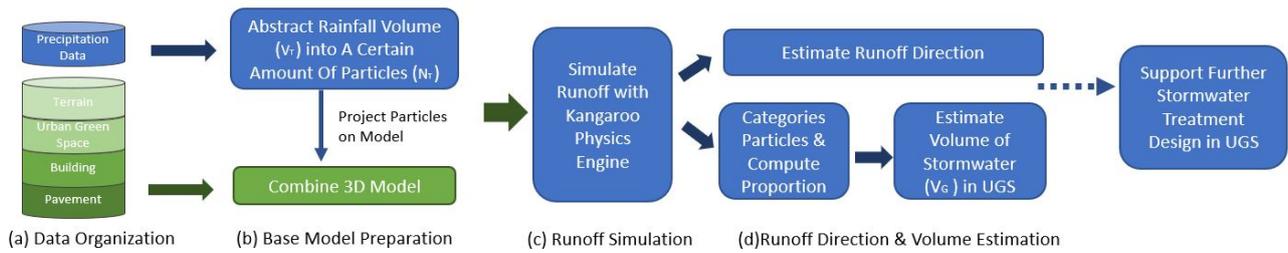


Figure 2. Research Framework Diagram

(2007) has proved that a 10% of UGS increase on-site can reduce by 4.9% (or 5.7%) of runoff based on a case study of residential area in Greater Manchester(Gill et al., 2007). The particle system movement simulation treats the topography as a uniform impervious surface, so completely ignoring the green cover influence on runoff, it is hard to get an accurate stormwater volume estimation.

### 3. DESIGN METHOD AND MODELLING

#### 3.1 Framework

To support the green stormwater management design work easier, this study adopted the particle system method to integrate runoff direction simulation and stormwater volume estimation within a well-known design platform - Rhinoceros 3D + Grasshopper. The work flow includes four steps (see Figure 2):

(a) *Data Organization*: The data organization followed the City Geography Markup Language (CityGML) which is the optimal 3D spatial information standard (van den Brink et al., 2013). With CityGML, we manage diverse data and relevant features in a common data model to avoid the time cost of data converting when we integrate the runoff simulation with other UGS spatial analyses(van den Brink et al., 2013). Due to the application domain extension mechanism, CityGML can feed the professional hydrology models as well. However, the professional models require several types of data including hydrology, meteorology, survey data etc. (Gironás et al., 2009), so we need to prepare at least three extra modules of data, which are weather, drainage pipeline systems and Subcatchment(Shen et al., 2020). Compare to the professional model, this model includes four extendable classes of topographic data and one class of hydrology data obtained from open access local precipitation data. The four classes of topographic data include terrain, land use (green space), site (buildings) and transportation. They are the common analysis data always used in urban planning and landscape design. The terrain, building footprint, UGS and transportation area are saved in surface data type. The precipitation data are stored as float.

(b) *3D Model Preparation*: It consists of two steps. The first step is data integration to create a topologically valid 3D model. Considering the influence of buildings on runoff track, we replaced the original terrain with a mixed-integer quadrangulation by combining the building footprint with the terrain mesh (see Figure 3). However, the generated buildings based on building footprint and height data always sink into or float over the terrain rather than perfectly sit on the topography. Thus, the 3D data integration and management referred to the work of Yan et al.(2019)and Li et al.(2020) (Yan et al., 2019, Li et al., 2020). As we have the georeferenced building footprint data and point cloud as the input, we preprocessed the point cloud data and classified the roofs based on footprints. After projecting the building roofs/footprints on the terrain, We got the intersection

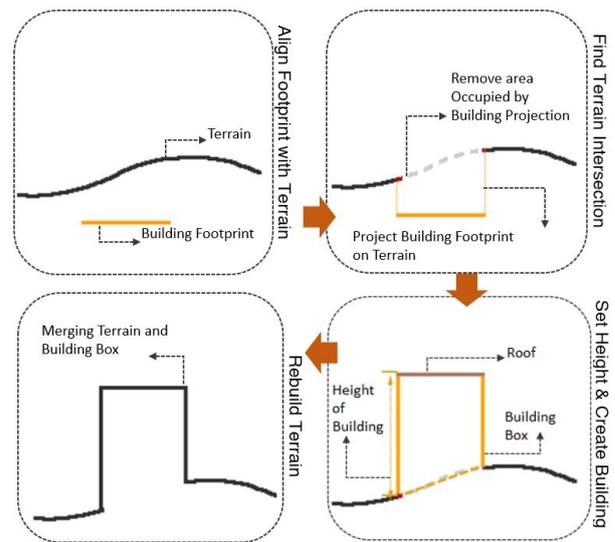


Figure 3. Process of 3D Modelling Based on Building Footprint and Terrain Mesh

curve of the building to the terrain, namely TerrainIntersection-Curve (TIC) (Gröger et al., 2012). Then, we shaped the buildings by pulling up the TIC to the roofs and remove the area of terrain covered by generated buildings. Finally, we merged the buildings and the edited terrain as an alternative terrain to facilitate further runoff simulation (see Figure 3). The second step is translating stormwater into particles and projecting them on the 'merged terrain'. We calculated the stormwater volume ( $V_T$ ) based on depth of rainfall ( $D_r$ ), and translated the volume ( $V_T$ ) into particle number ( $N_T$ ) by defining a particle radius ( $R_p$ ) (see Equation 1). Then we generated the corresponding number of particles and projected them on the building roofs and exposed terrain surface.

$$V_T = D_r S_T; N_T = \frac{V_T}{(4/3)\pi R_p^3} \quad (1)$$

where  $V_T$  = total stormwater volume(cubic meter)  
 $D_r$  = depth of rainfall(meter)  
 $S_T$  = site area(square meter)  
 $N_T$  = total number of particle (integer)  
 $R_p$  = particle radius(meter)

(c) *Runoff Simulation*: Runoff simulation was conducted with the Kangaroo physics engine (Morschek et al., 2019). By iterating the projected particles moving 'downward' on terrain, we got the movement track of these particles (runoff track).

(d) *Runoff Direction & Volume Estimation*: With the particle movement track, we estimated the direction and volume of runoff in inundation areas separately. Following the law of conservation of mass (Puri, 1996, Morschek et al., 2019), the total quantity of particles does not change during the simulation. Thus, the proportion of particles in the inundation areas can indicate the distribution of stormwater quantity on-site.

It is worth noticing that, compare to runoff direction simulation, the way of estimating stormwater volume with a particle system is still a challenge. There are two questions: (1) How to design a rainfall event as input for the stormwater analysis model to reflect local hydrologic environment? (2) How to integrate the infiltration features of the land cover into the model?

### 3.2 Design rainfall event

Due to the variation of stormwater conditions in different climate environments, this study set the total stormwater volume based on the local rainfall database. Liu et al. (2016) have confirmed that more than two-thirds of the total annual runoff volume is generated by frequent recurring rainfall events (with a smaller than 6-month average recurrence interval (RAI)) (Liu et al., 2016). Thus the research community and local governments define WSUD as the facility capturing stormwater of small frequent rain events and reducing the flow of excessive rain events (Zhang et al., 2019, McPhail et al., 2017). Thus, this study computed the stormwater quantity based on the depth of a frequent rainstorm (RAI smaller than 6 months) with a short duration (1-2 hours).

### 3.3 Integrate Infiltration Features

As discussed above, the natural and artificial land covers have different effects on runoff generation. Therefore the hydrology engineering adopts an infiltration coefficient and infiltration rate to describe the different soil types' hydrologic features (Pauleit and Duhme, 2000, Zhang et al., 2020, Nachshon et al., 2016). To simplify the computation, we assume we have two types of land cover, i.e. UGS and pavement. WSUD design mainly focuses on passive capturing and treating frequent small rain, so we hypothesised that the UGS will capture all stormwater getting in. On the contrary, the artificial cover is mainly impervious, so we assumed the artificial pavement will not absorb any stormwater. Thus, the key point of stormwater volume computation is categorising particles to identify the proportion of particles distributed to treat in UGS. During the model testing process, we conducted two steps (see Figure 4):

*STEP 1*: According to the stop position of the particles, we categorised them into *PO* (particles stopped outside of UGS) and *PI* (particles stopped in UGS). And we computed the corresponding particle number  $N_{PO}$  and  $N_{PI}$ .

*STEP 2*: Considering the infiltration features of UGS, we re-categorised *PO* and *PI* particles into two sub-groups separately. If *PO* particles passed through one/multiple UGSs before stopping, we categorise them as *PO-2* and distribute their number belonging to the first UGS they passed. If not, the particles are *PO-1*. As for the *PI* particles, if they passed only one UGS, they belong to *PI-2*. If the particles passed multiple UGSs, we categorise them as *PI-1* and distribute their number to the first UGS they passed. We computed the corresponding particle number  $N_{PO-1}$ ,  $N_{PO-2}$  and  $N_{PI-1}$ ,  $N_{PI-2}$ .

With the particle categorisation and number computation, we calculated stormwater quantity in UGS based on the following

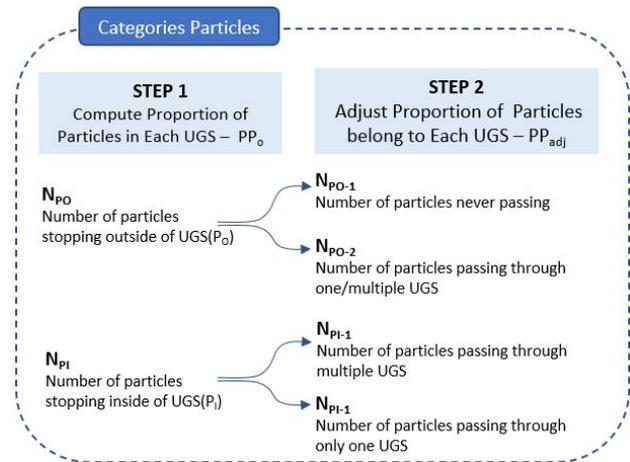


Figure 4. Particle Categorisation

equations:

$$PP_o = \frac{N_{PI}}{N_T} 100\%; \quad (2)$$

$$PP_{ad} = \frac{N_{PO-2} + N_{PI-1} + N_{PI-2}}{N_T} 100\% \quad (3)$$

$$V_G = PP_{ad} V_T \quad (4)$$

where  $PP_o$  = proportion of particles stop in UGS (%)  
 $PP_{ad}$  = adjusted proportion of particles belong to UGS (%)  
 $N_{PI}$  = number of particles stopping in UGS (integer)  
 $N_{PO-2}$  = Number of particles passing through one/multiple UGSs before stopping outside (integer)  
 $N_{PI-1}$  = Number of particles passing through multiple UGSs before stopping in a UGS (integer)  
 $N_{PI-2}$  = Number of particles getting in a UGS and stopping in it (integer)  
 $V_G$  = volume of stormwater to be treated in UGS ( $m^3$ )

### 3.4 Model Test

In the above framework there are three parameters: depth of rainfall, radius of particle and iteration time for runoff simulation. Among them, the depth of rainfall is computed on the basis of rainfall event. As the different events bring different stormwater volumes, they will generate different particle quantities. It is also not clear whether the different particle numbers will impact the simulation result. Similarly, the different radii of particles will generate different particle numbers as well. In addition, the different iteration times would impact the stopping locations of particles. Therefore, this study organised three types of tests for the three parameters respectively.

The first test relates to the different iterations to analyse the number variation of particles in UGS. We assume if the number does not change then the result is stable and you can stop the iteration. The second test focuses on the variation of rainfall events. This study intends to verify whether the different precipitation inputs will generate different results. In the third test, given the same rainfall event and iterations, we tested whether the results will be varied with the radius change.

## 4. CASE STUDY

The framework was tested at two sites. Test site 1 is an irregular rectangle site with around 380000 square meters. The

site has a significant downward slope from south to north (see Figure 5-1). Test site 2 is a square site almost half-size of test site 1 (160000 square meters). There is a gentle slope inward from all sides on test site 2 (see Figure 5-2). To test the organised framework, we selected UGSs over 500 square meters in the two cases and name them from UGS 1 to UGS 12 and UGS 1' to UGS 7' separately (see Figure 5). Regarding the hydrological data, we referred to the Sydney Design Rainfall Depth table in Design Rainfall Data System (2016) as the precipitation input which is developed by the Australian government based on a more extensive database. Besides, to test the feasibility of the integrated framework in daily design work, this framework is tested on a customary computer for graphic design (i7,5.0GHz,32G RAM).

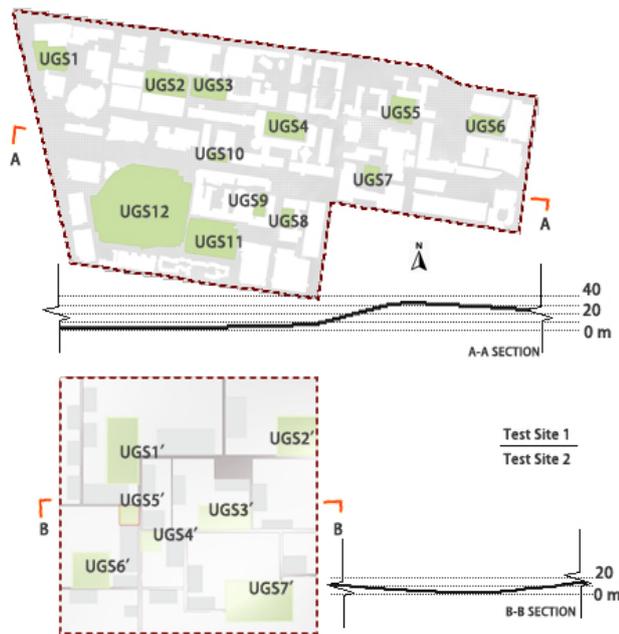


Figure 5. Simulation Site Introduction

#### 4.1 Iteration Times

With the same particle radius (50cm) and 17 mm depth of rainfall event (4 Exceedances per Year (EY) with 1-hour duration), we set a series of simulations with different iterations to test the integrated model on test sites 1 and 2. As we assumed the variation of particle numbers is more obvious at the early stage of iteration, we set simulation iteration times as 100, 200, 300, 400, and 500. After 500 iterations, we set the number of iterations as 1000, 2000, 3000, 4000, and 5000 for simulations (shown as the X-axis of the line charts in Figures 6(1) and (2)). We computed the quantity variations of particles in UGSs for each simulation (shown as the y-axis of the line charts in Figures 6(1) and (2)) to check when all the particles would be stable. Except for computing the particle numbers in UGS, we captured the final frames for each simulation to check the stable situation of particles by comparing the particle locations.

The simulation shows that our hypothesis is confirmed. For both sites 1 and 2, with the 100 to 500 iterations, the particle quantity (see Y-axis of the line charts in Figure 6) fluctuated obviously. For site 1, the particle number changes in UGSs became small in the simulation with 2000 iterations (see line chart in Figure 6(1)). Then the particles were stable in the simulations with 3000 iterations and more. The line chart for site 2 (see Figure 6(2)) shows that the variation of particles in Site 2 became small in the simulation with 2000 iterations, except for

UGS 5'. UGS 5' is a small green space located at the bottom of the terrain and surrounded by buildings. Figure 6 (2) shows that the particle numbers in UGS 5' kept changing until simulation with 4000 iterations. The series of final iteration frames in Figure 6 also prove the variation of particle numbers in UGS. In the simulations for the two sites, the location of particles changed obviously from the 100 to 500 iterations. In the 1000 iteration frame, most of the particles have been stable. From the 2000 to 5000 iterations, the variation of the particle locations is hard to identify visually.

The test shows that the iteration times required for particles to be stable are affected not only by the size of the study site but also by the slope gradient and the complexity of the surrounding built environment. However, we can get an accurate result with 4000 iterations or more in general. Considering the simulation time efficiency, in the following simulation tests, we set the iteration times as 4000.

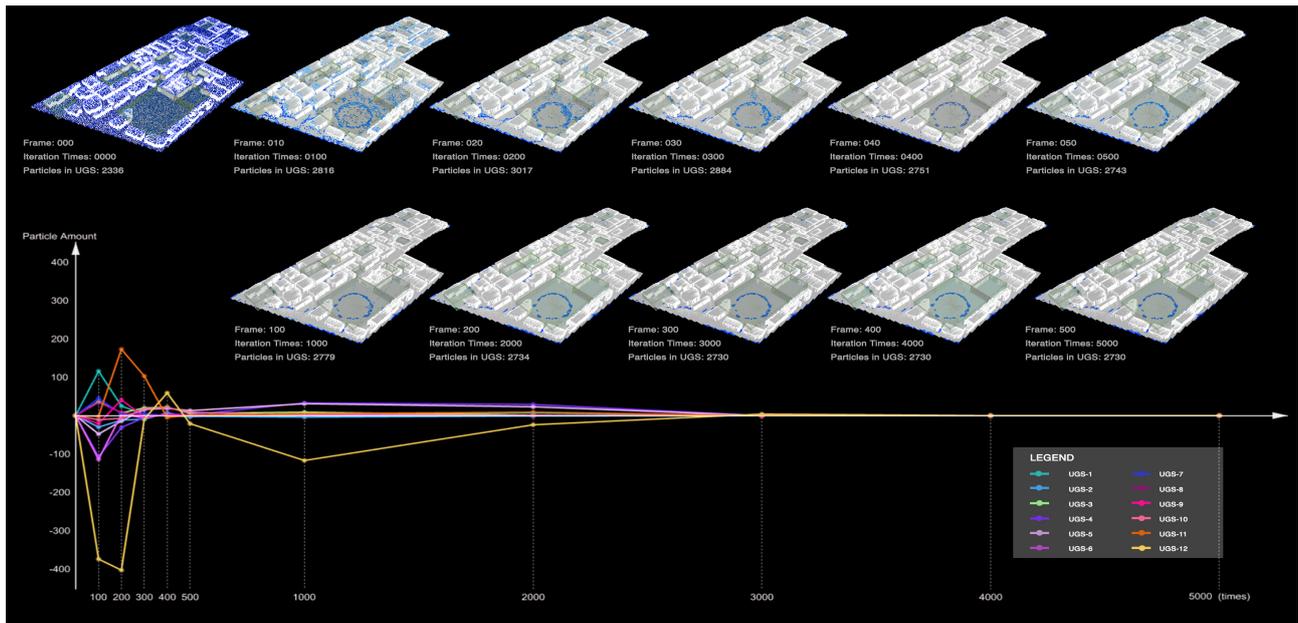
#### 4.2 Rainfall Event Testing

This study considered not only frequent rainfall events but also infrequent rainfall events. For the frequent rainfall events, we collect a series of 4 EY rainfall event data (duration ranging from 1 minute to 168 hours) for the test to check whether the simulation results can keep the same. As the computation of the infrequent rainfall event is a computation-intensive task, we just collected three events from 1% Annual Exceedance Probability (AEP) rain events. They are events with a duration of 30 minutes, 1 hour, and 1.5 hours. For the runoff simulations on the two sites, we set the same particle radius (50 cm) and iterations (4000).

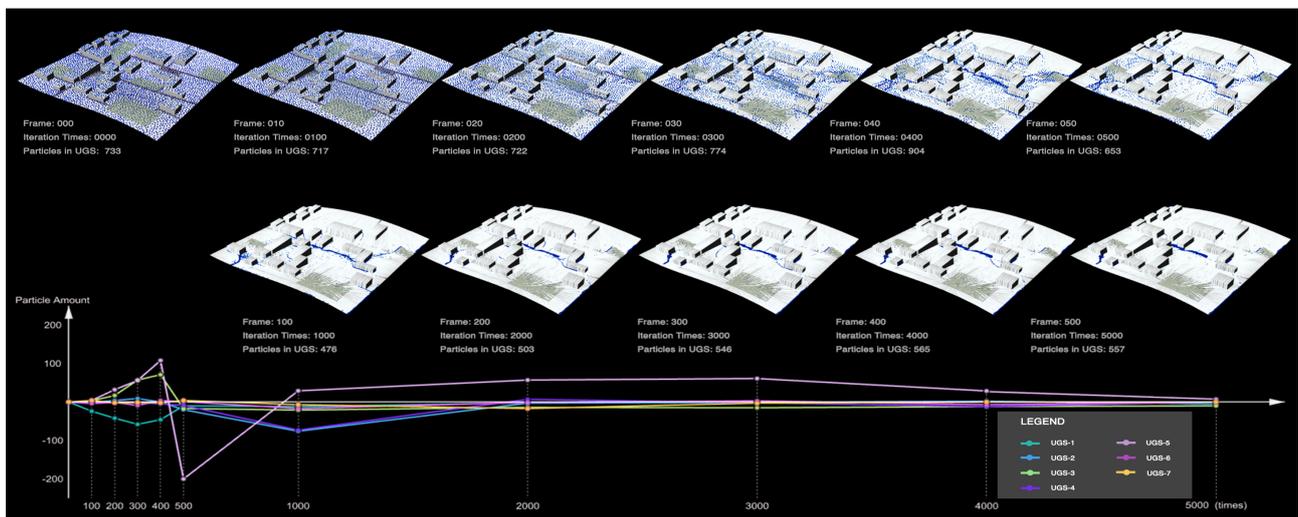
To test the influence on the results from infiltration features of land cover, we organised two parts of data analysis. One is calculating  $PP_o$ : the proportion of original particles stopping in UGSs directly (see Figure 7,8(1)). The other one is calculating  $PP_{ad}$ : the proportion of adjusted particles belonging to UGSs (see Figure 7,8(2)). In Figure 7 and 8, X-axis and Y-axis represent the time duration of rain events and volume proportion of stormwater in UGSs separately. In addition, to distinguish from the results of frequent rainfall events, we marked the area for the results of infrequent rainfall events and linked the results dash lines.

Compare the line chart (1) to (2) in Figure 7 and 8, it shows that the stormwater volume in UGS 7, 8 in site 1 and UGS 7' in site 2 are zero. The terrain analysis shows that the location of UGS 7, 8 and UGS 7' is on the top or middle of the slope, so the particles followed basic laws of physics to move downward and leave the UGSs. However, this result conflicts with our passive treating stormwater theory because we assumed the UGS will harvest the rainwater getting in. It proves that we cannot use the proportion of original particles gathered in the UGSs to estimate stormwater volume directly. Meanwhile, the results of short duration rainfall event (from 1 to 45 minutes) for the UGS 11 in Figure 7(1) and UGS 4',5',6' in Figure 8(1) are zero as well. For the rainfall events with around 1-hour or longer duration, the analysis results show a certain amount of particles staying in these UGSs. Thus, the tests indicate that too small number of particles distributed on-site would miss some variation of topography and cause an inaccurate result.

In addition, compare to the diagram (1) in Figure 7 and Figure 8, diagram (2) shows that every UGS collected a certain quantity of stormwater which is relatively closer to the reality. In addition, although the analysis result slightly fluctuates, the proportion changes of stormwater stay within around 1% slot. The obvious value changes are mainly generated by the rainfall events shorter than an hour. As for the infrequent rainfall event



(1) Iteration Times Testing For Test Site 1



(2) Iteration Times Testing For Test Site 2

Figure 6. Simulation Result With Different Iteration Times

testing, the simulation displays that the proportions of stormwater volume stay in the same value variation slot of frequent rainfall event testing. Yet, 1% AEP rainfall events have been classified as flooding (Alexander et al., 2019), so the UGSs are impossible to retain the same proportion of stormwater in flooding events with the small rainfall event on-site. Therefore, the test reveals that the runoff simulation based on the particle system is not quite sensitive to rainfall event selection. Once the generated particles reach a certain amount, the simulation result is similar. Considering the cost-efficient of computation, we chose the 1-hour duration rainfall event as the following test input.

### 4.3 Particle Size

We tested five groups of particle radius from 70cm to 30cm for the two study sites with the 17 mm depth of rainfall event (4EY, 1 hour) and same iteration times (4000). We found the amount of generated particles varied obviously from around 4000 to almost 60000 based on the radius setting. When we tested the runoff simulation with 20cm radius particles, as a group of data would be recorded for every iteration during the

process, the computer warned 'out of memory' after 75% iteration was done. Thus, the too small radius would cause over intensive computation.

Figure 9 and Figure 10 show the particle size test on site 1 and 2 separately. In both line charts, the X-axis represents the particle radius varying from 70cm to 30cm, and the Y-axis is the volume proportion of stormwater in UGSs. The line charts show that the value variations for the different rainfall event simulations keep similar. The relatively obvious value variations mainly happened in the runoff simulation with 60 and 70cm radius particles. The result proves that as long as the number of particles is not too small, the simulation results are similar. Compare to other UGSs, UGS 12 in Figure 9 and UGS 3' in Figure 10 have the most particles and fluctuate most obviously. Both the two UGSs are located at the bottom of the research site and have a relatively large area. The simulation result reminds us, that in the further analysis and design of this type of UGS, we should be aware of setting a tolerance for the UGS stormwater harvesting ability.

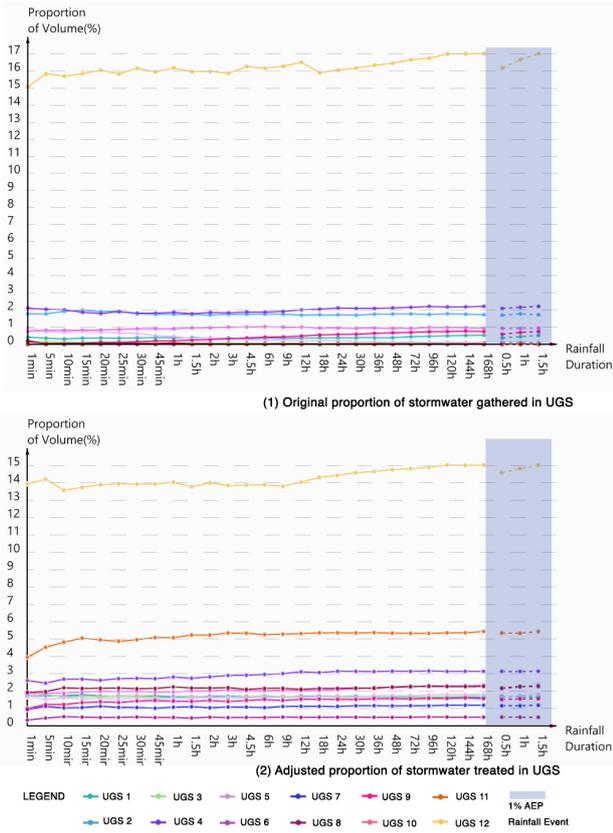


Figure 7. Rainfall Events Testing Result For Test Site 1

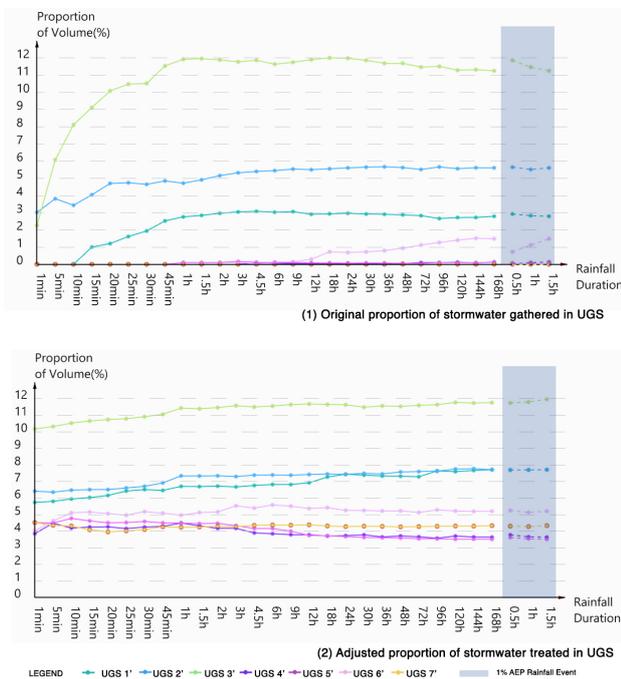


Figure 8. Rainfall Events Testing Result For Test Site 2

#### 4.4 Discussion

The three tests of the above three parameters (number of iterations, rainfall depth, and particle size) confirmed our hypothesis that the three parameters affect the runoff simulation

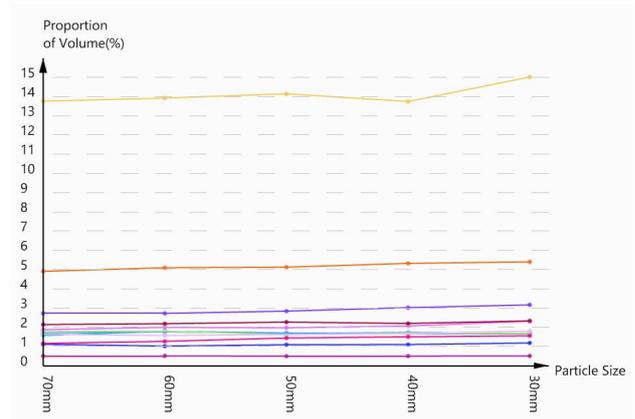


Figure 9. Particle size Testing Result For Test Site 1

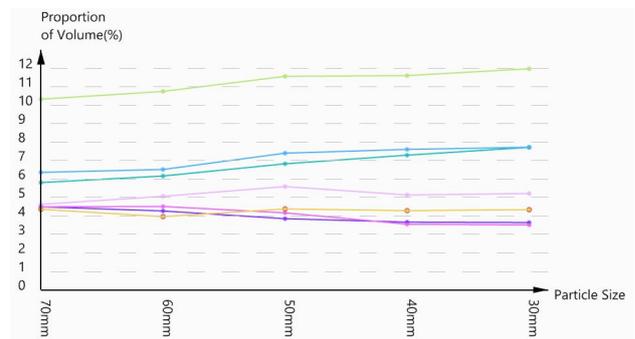


Figure 10. Particle size Testing Result For Test Site 2

results to some extent. The iteration time represents the time step of particle motion. An iteration time setting that is too small will cause particles to stay on their path toward the bottom of the terrain. In consequence, such iteration time settings will lead to inaccurate simulation results. Based on the above test, 4000/5000 iterations are enough for the particles to roll down to the lowest points generally. Particle event input (rainfall depth) and particle size impact the simulation result by the particle amount generated. The simulation result shows, that once the particle number is set too small (less than 10,000), the result values fluctuate obviously. Although, larger particle numbers need more time for simulation. Even when the particle quantity is up to over 50000, the customary computer reporting 'out of memory' would be probably more common. Besides, the two testing sites are precinct scale sites. Therefore, to keep an appropriate balance between the accuracy and computation speed of this model, we recommend conducting the integrated simulation with around 10,000 to 20,000 particles for precinct scale sites.

In addition, the runoff simulation with particle system is an abstracted method developed based on point-based animation (Nealen et al., 2006). As the abstracted features, it simplified the stormwater volume computation process without considering the influence of rainfall duration and land cover features. However, this study targets WSUD design, so the rainfall event would have a 'default setting' which is a frequent rain with a short duration rather than a flooding disaster (Zhang et al., 2019). Thus, the 'default setting' has weakened the influence brought by ignorance of rainfall duration settings. With the premise, we tested including infiltration features of land covers into the calculation of particle proportions. The study proves that the simulation with consideration of infiltration factors is closer to reality than the original runoff simulation.

## 5. CONCLUSION

This paper presented an integrated method to quantitatively analyse the stormwater management needs in UGSs. Compare to the professional hydrological models, this model has the following three advantages:

(1) *friendly for urban planners and designers*: The model is conducted the quantitative stormwater analysis on the popular 3D modeling platform Rhino + Grasshopper which is a well-known spatial design platform. It facilitates the planners and designers to conduct stormwater analysis and UGS design in a common design model.

(2) *easy for data collection and organization*: As the input data of the model is the regular data in urban space analysis and design. The data is organized following CityGML which is popular in geospatial analysis and urban planning field. Thus, for urban planners and designers, the data collection and organization is not a challenging work. Furthermore, the integrated characteristics of the model reduced the possibility of data conversion.

(3) *quantitative for the stormwater analysis*: By linking the proportion of particles in UGS to the proportion of stormwater, we estimated the stormwater volume. Besides, the particle categorisations help us to introduce infiltration features of UGS into the model which makes the simulation closer to reality.

In general, due to its cost-efficient and easy operation features, it is still a good choice to support the preliminary UGS design. However, this study haven't done the validation for the abstracted stormwater analysis based on the particle system with the professional hydrological models. This would be one of the further works. we will conduct SWMM analysis with the same spatial data and compare the results to the integrated model output to evaluate the accuracy of the model. In addition, this study triggers us to consider integrating more detailed infiltration features into the runoff simulation model to provide more accurate estimations of runoff. Furthermore, the study also provides the possibility to integrate other hydrologic parameters into the model. In the next step of research, we will explore integrating the runoff coefficient in the model to make the simulation more sensitive to the intensity of the rainfall events.

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