Three-dimensional simulation of regional urban waterlogging based on high-precision DEM model

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Abstract: In order to deal with the urban waterlogging disasters, a high precision three-dimensional (3D) Digital Elevation Model (DEM) is built in this paper. This DEM is based on high-precision data of urban topography and geomorphology, covering 3D surface elevation, road network and structures. The simulation calculation of this model can get different watershed area according to different elevation based on the topographic feature. Furthermore, divide the urban regional model into the stage sub-catchment area corresponding to the elevation. Within the sub-catchment area, it can also reflect the situation of urban waterlogging, in combination with the rainstorm intensity formula, the statistics of local area underlying surface, and Soil Conservation Service (SCS) model of runoff simulation. It can also help to simulate the submergence depth and range under different recurrence stages of rainfall scenarios. The research shows that this DEM model can provide the premise for the highly accurate numerical simulation of surface runoff and confluence, which can effectively improve the accuracy of the division of catchment area and the assessment, prediction of waterlogging disaster. This provides an important idea and method for the flood prevention and control in flood season for reservoir, tailings pond and urban waterlogging.

Keywords: urban waterlogging, high-precision DEM model, three-dimensional GIS, disaster simulation

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1. Introduction

With the increase of the cities' area and the appearance of big cities, the landform of cities has been changed. According to the statics, the area of lakes in the southern cities of China cities has reduced by 50 percent in the past seventy or eighty years. Taking Wuhan for example, from 1987 to 2016, the area of lakes in Wuhan's main urban area shrank by a total of 128.28 km^2, and the closer it is to the urban building area, the more obviously the lake area shrank; the smaller the lake area, the more filling phenomenon [1]. In addition, the change of urban geomorphology has broken the balance of rainfall and evaporation and the frequency of extreme weather caused by global climate change has increased in recent years. Due to these two reasons, urban waterlogging has become a common disease in many southern cities in the rainy season. The domestic waterlogging situation in recent years is as shown in Table 1. Many urban waterlogging cases show that urban waterlogging disasters with regional characteristics, which happens at city small low-lying area. So studying the distribution of regional waterlogging in different rainfall recurrence and generating strategy of preventing waterlogging is of important value to reducing the economic loss and improving residents' life and property safety.

Tab.1 Urban waterlogging of Chinese cities in recent years

Year	Disaster Region	Total Rainfall(mm)	Loss（￥100 million）
2013	Sichuan Province	170	53.7
2014	Shenzhen	318	0.8
	Hunan Province	315.2	25.8
2015	Wuhan	197	0.68
2016	Wuhan	560.5	22.65
2017	Hunan Province	435	385.1
2018	Chengdu	306.4	24

Significance and Novelty of This Research

In recent years, with the development of computer science, some scholars firstly put forward models such as SWMM, UCURM, MOUSE, STORM and WALLINFORD, all of which have achieved good application effects [2-4]. In China, Chinese scholars have also made many efforts. For example, simulation system of rainstorm waterlogging in Tianjin City developed by Qiu and others in 2000, based on the two-dimensional unsteady hydraulics model and combined with the monitoring of rainfall information, simulated urban waterlogging, which is the first well-known waterlogging simulation system in China [5,6]. But its spatial analysis ability is weak. Later, Wang established an urban waterlogging disaster analysis model by using GIS in 2004, which further solved the problems encountered by Qiu [7]. Since then, the study of waterlogging in China has entered an era of rapid development. Scholars have combined GIS with various waterlogging models and verified them in big cities, which achieved good results. For example, Ye constructed flood inundation model and established urban road-waterlogging-zone map [8]. Jing carried out risk analysis of waterlogging disaster simulation by GIS technology [9]. However, in most of the previous studies, the research areas are mostly large-scale areas. In 2010,

Yin proposed a small-scale urban waterlogging simulation, which shrank the study area form an entire city to a single administrative region, while no more small-scale waterlogging simulation was carried out [10]. By combining the rule of urban waterlogging occurred in recent years, the influenced area of waterlogging is usually small. While the simulation precision of waterlogging in large-scale region is not enough, which is unable to locate precisely to disaster area. And the DEM data used is often 30m by 30m raster data, which cannot construct a high precision terrain model. However, in the study of waterlogging, DEM model is the foundation of dividing catchment area and simulate the runoff.

To sum up, it can be seen that the current urban waterlogging simulation methods are mainly combined with spatial geographic information, rainfall and urban drainage pipe network to simulate the surface runoff and confluence process, which have been relatively mature. However, the research areas are mostly large areas, and there are few researches on waterlogging in small areas such as factories and schools. In addition, on the issue of dividing catchment area, the previous research is mostly based on drainage pipe network, no actual consideration of terrain characteristics. In this paper, watershed is extracted according to high-precision DEM model and topographic features, which divide the study area to different catchment areas. And simulate the disasters in each area. Finally, three-dimensional visualization technology is used to display the simulation results. This method can be used to understand the disaster in the region more intuitively and accurately. This paper further expands the research ideas and methods of urban waterlogging disaster, and provides reference for the simulation and early warning of waterlogging in small areas.

2. Research ideas and methods

High-precision 3D DEM data is an important data basis for the study, in order to ensure the model accuracy and facilitate the high-precision topographic mapping. The research area of this paper is located in Zhongnan University of Economics and Law, Wuhan, China. This area is low-lying and waterlogging disasters occur in every year's rainstorm season, especially in 2016. As shown in Figure 1, waterlogging depth in the building exceeds 50cm, resulting in a loss of 2.36 million of equipment caused by flooding.

Figure 1. The condition of waterlogging in 2016

2.1 Overview of the model area

Wuhan, located in central China, has a humid north subtropical monsoon climate with abundant rainfall, sunshine, hot summer and cold winter. There is more rainfall in the plum rain season in early summer. The annual rainfall is 1100 mm.

The waterlogging prone season is from June to August. This paper takes Zhongnan University of Economics and Law as study area. The total area of the study area is $1.11km^2$, and the land types are mainly divided into building land, road, grassland and lake. There are 67 buildings, covering a total area of $0.49km^2$, including two teaching buildings, 8 administrative office buildings, 17 dormitory buildings for students and 16 dormitory buildings for teachers. Roads, greenery and lakes cover an area of $0.49km^2$, $0.20km^2$ and $0.11km^2$ respectively.

2.2 Study framework

The study framework of this 3D DEM urban waterlogging model simulation is shown in Figure 2.

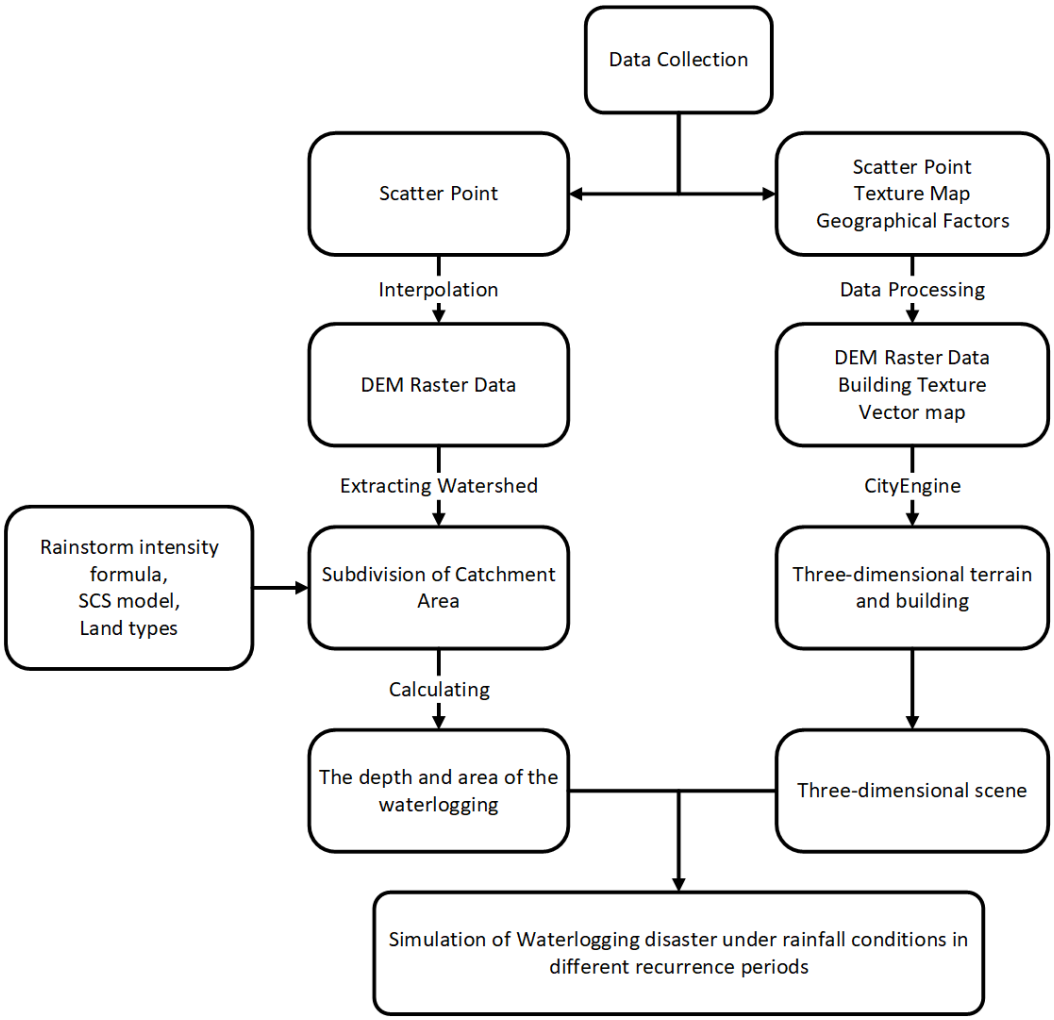


Figure 2. Framework of waterlogging simulation

2.3 The watershed extraction method

The watershed is the basis for dividing the catchment area. The runoff on both sides of the watershed flows in their respective areas and cannot be collected. Based on high-precision DEM data and the flood simulation method from bottom to top of surface elevation difference, the boundary of different sub-catchment areas can be found, the watershed of the study area is extracted automatically, and then the catchment area is delimited.

2.3.1 High precision terrain model

In order to ensure the accuracy of the data, the millimeter-level GPS measuring instrument was used to obtain the

elevation data points. After field measurement, artificial modification and expansion are carried out according to the actual terrain to generate a 0.7m×0.7m High-precision DEM model.

2.3.2 Automatic watershed extraction method

In the computer, we can read DEM raster data into a two-dimensional array, each raster has a unique identification, and each value in the array is the elevation value of the raster. The raster data principle is shown in Figure 3.

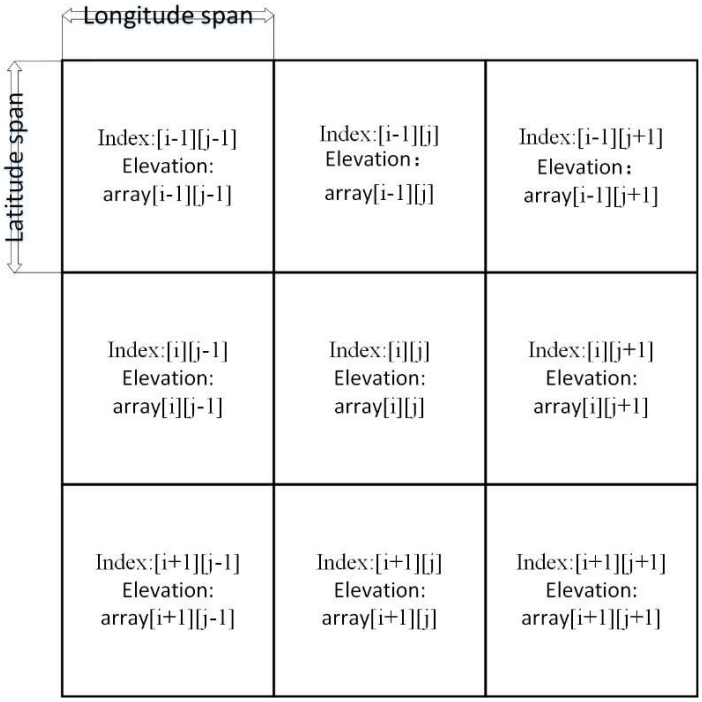


Figure 3. Principle of grid data

Watershed extraction algorithm is to use different height of the plane to cut raster data to find the region lower than the plane. As the cutting plane is raised continuously, the number and range of areas will increase continuously. When two or more regions are about to intersect, because the terrain is continuously changing, we can get a continuous boundary, and the boundary is the watershed of the research area. The study area is divided into several sub-catchment areas. The principle is shown in Figure 4.

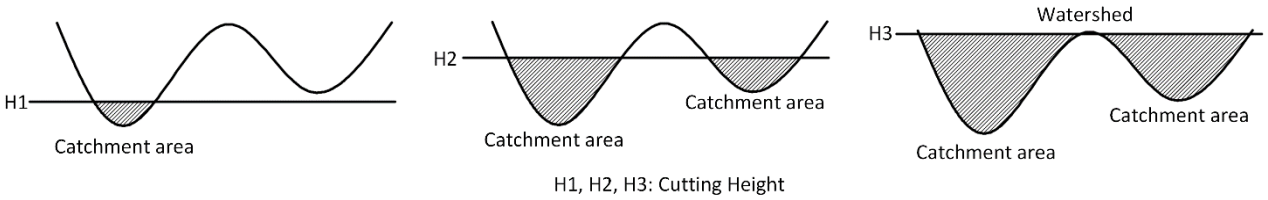


Figure 4. Principle of extracting watershed

Watershed extraction algorithm is implemented by Python programming. The algorithm flow is described as follows:

(1) Read the DEM raster array. Find the minimum and maximum values in the array. Define the starting and ending height of the cutting plane and a new catchments array to hold the region which is lower than the cutting plane found in the

loop. Define a new array which have the same number of rows and columns as the original grid array to save the watershed.

(2) Define the cutting height as the starting height, judge whether the cutting height is less than or equal to the ending height, and then enter the loop.

(3) After entering the loop, traverse the original raster array. If the elevation value of a point is less than or equal to the cutting height, change the value of that point in the catchment area array, and find the region under the cutting height.

(4) Traverse each point in the catchment area array, iterate through the points in the certain area in 8 directions, and divide different areas with different numbers.

(5) Traversing the array of catchment areas, if there are points of two regions in the eight grids around a certain point, the point is the point in the watershed of two regions, and the point is saved in the watershed array.

(6) As the cutting height increases, judge whether the cutting height is less than or equal to the termination height; if it is true, continue the loop (3) - (5); if not, jump out of the loop and cut the original raster data according to the index value of the watershed array, and output the array of sub-catchment areas after cutting.

2.4 Urban waterlogging disaster model

2.4.1 The rainstorm intensity formula

The rainstorm intensity formula is the premise to study urban waterlogging disaster. According to the Design Specification for Outdoor Drainage, the formula of rainstorm intensity is defined as follows:

$$q = \frac{167A(1 + C \lg p)}{(t + b)^n} \quad (1)$$

Where: Q is the intensity of the storm, $L/s.hm^2$; A is rainfall, mm; C is the variation parameter of rainfall, which is one of the parameters reflecting the variation degree of rainfall intensity in different recurrence periods; P is the designed rainfall recurrence period, a; T is rainfall duration, min; b and n are constants, which reflect the changes of rainfall intensity over time.

2.4.2 The SCS model

The SCS model is based on the basic assumption that the ratio of the actual infiltration capacity to the potential storage capacity of catchment area is equal to the ratio of the actual surface runoff volume to the maximum possible runoff volume of catchment area, which can be expressed as Formula 2.

$$\frac{F}{S} = \frac{R}{P - I_a} \quad (2)$$

Where: R is the runoff, mm; P is rainfall, mm; I_a is the initial lower volume, mm, including closure, surface water storage, etc. F cumulative infiltration, mm; S is the maximum possible stagnant flow in the basin, mm.

The relationship between the initial loss and the maximum retention can be expressed as a first-order linear relationship, and the relationship between the two is verified by the U.S. Soil Conservation Service through a large amount of rainfall data, as shown in Equation 3.

$$I_a = 0.2S \quad (3)$$

Then according to the principle of water balance, the calculation formula of runoff is shown in Formula 4.

$$R = \frac{(P - \ 0.2S)^2}{P + 0.8S} \quad (4)$$

To calculate the maximum retention S, the parameter CN is brought in. The value of CN is only related to the soil type and land type under the basin. The relationship between the two is shown in Equation 5.

$$S = \frac{25400}{CN} - 254 \quad (5)$$

The value of CN is generally an integer less than 100. It can be seen from the above formula that the greater CN is, the greater the runoff will be generated. The CN values corresponding to different land types can be obtained by looking up the table.

2.4.3 The process of confluence disaster

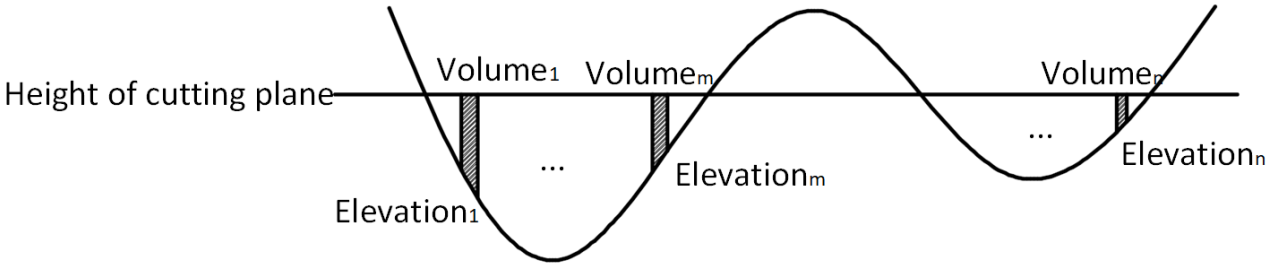
After the rain falls, it first passes through the interception of plants, the storage of depressions and the infiltration in soil. When the rainfall makes the natural storage saturated, the rain starts to flow along the surface slope. If the rainfall continues to increase, the scope of the diffuse flow will also increase, forming a comprehensive diffuse flow. Under the influence of gravity, water flows to the lower terrain and gather, then enters the urban drainage pipe network. When the urban drainage pipe network is unable to discharge all the runoff generated by rainfall, that is when the runoff volume is greater than the displacement volume, waterlogging disasters will occur in the lower terrain. The numerical difference between the runoff volume and the displacement volume is the disaster-causing volume, and the relationship among the above three factors can be expressed in Formula 6.

$$W = R * S_1 - D * S_2 \quad (6)$$

Where: R is the runoff of rainwater , mm; S_1 is runoff area, mm^2; W is the amount of disaster, mm; D is the ability of underground drainage system capacity system, mm/h; S_2 is the drainage area, mm^2.

2.4.4 The calculation of submergence depth

For a sub-catchment area, it can be considered as a container whose height of the water corresponds to the volume of the water. That is to say, for a certain disaster-causing volume W, there is a corresponding submergence depth H in the catchment area. Based on the certain disaster-causing volume, the water volume of each grid in the DEM raster data of different heights can be calculated, and then the total water volume can be obtained by summation. The volumetric principle of DEM raster data is shown in Figure 5.



144

145 **Figure 5. Principle of calculating the volume of DEM data**

146 The volume calculation formula is as follows in Formula 7:

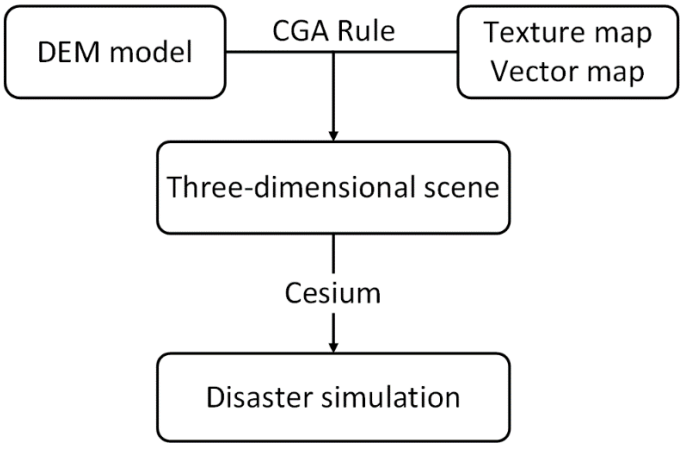
147 $$V = \sum_{i=1}^{n} S_{cell} * (H - h_i) \quad (7)$$

148 Where V is the volume under fixed height, S_{cell} is the grid area, H is the fixed cutting height, and h_i is the i^{th} grid
149 elevation value.

150 Under a certain disaster-causing volume W, the lowest point was set as the initial cutting height H. If $W > V$, the step
151 length was increased to 0.01m. When the difference between W and V was the smallest, H was the height of the cutting
152 plane, and $H - h_{min}$ was the maximum waterlogging depth of the region.

153 **2.5 3D dimensional visual simulations**

154 The technical system of 3D modeling and disaster simulation in this paper mainly includes CityEngine and Cesium,
155 and the simulation steps are shown in Figure 6.



156

157 **Figure 6. Framework of 3-dim visualization**

158 CityEngine is a three-dimensional software to construct models, which has the following characteristics:

159 (1) With high modeling efficiency, CityEngine has a set of unique rules modeling methods, which can change the
160 modeling process into a code writing process, making it convenient and fast.

161 (2) With strong compatibility, model files generated by ArcGIS, 3DMAX, Sketchup and other software can be

imported to construct 3D scenes. The models created can also be exported to various common 3D model formats.

(3) It is suitable for the scene modeling within the city scope, but not for the detailed modeling of a single model.

Cesium is an open source 3d virtual Earth engine based on JavaScript. Cesium is designed to provide users with powerful map data display and related operations. Cesium can run in browser supported by the WebGL. In this paper, the Cesium is used to load the 3D model built by CityEngine, and its water surface simulation function is used to simulate the regional waterlogging disasters under rainstorm scenarios in different recurrence periods.

3. Application examples

3.1 Elevation data

Elevation data processing mainly includes interpolation processing, automatic watershed extraction and sub-catchment area division. The processing results are shown in Figure 7.

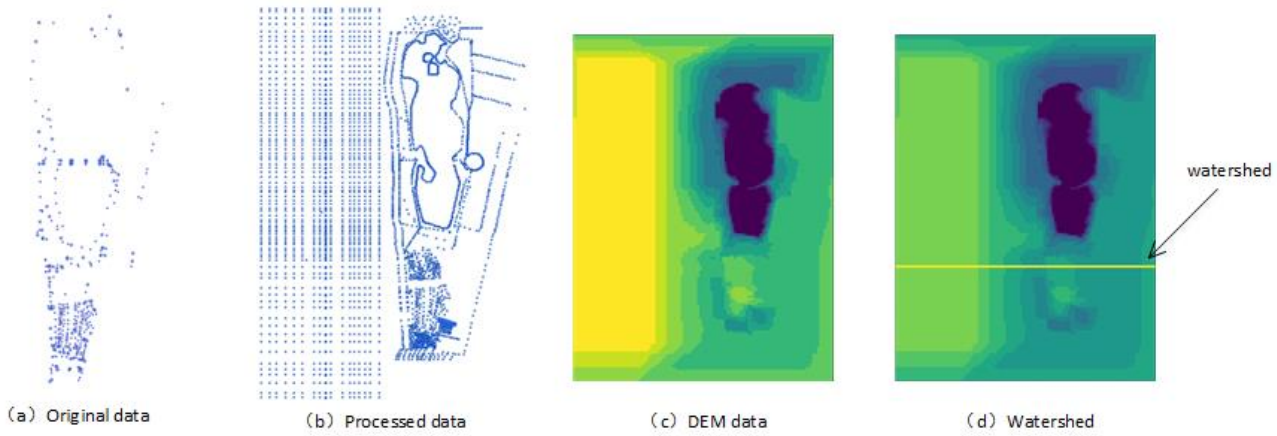


Figure 7. Results of processing the DEM data

The final results of watershed extraction are shown in the figure 6 (d). It divides the study area into two sub-catchment areas. The field observation shows that the division result of the sub-catchment area is coincide with the actual topographic features. The dividing line is a main road in the study area, which divides the study area into two sub-catchment areas of north and south region.

3.2 Data of waterlogging simulation

3.2.1 Rainfall information

According to the standards of Wuhan drainage and waterlogging prevention system, the intensity of short duration rainstorm in Wuhan should be calculated by the following formula:

$$P = 0.5\sim10a \quad q = \frac{885[1 + 1.58\lg(P + 0.66)]}{(t + 6.37)^{0.604}} \tag{8}$$

$$P = 10\sim50a \quad q = \frac{577(1 + 0.96\lg P)}{(t + 2.26)^{0.432}} \tag{9}$$

$$P = 100a \quad q = \frac{1057}{(t - 0.57)^{0.317}} \tag{10}$$

Where: Q is the intensity of the storm, $L/s.hm^2$; P is the designed rainfall recurrence period, a; T is rainfall duration, min.

The short-duration rainstorm is expressed by the rainstorm intensity formula and the rain peak coefficient. When the rainstorm recurrence period is 5-10a, the rain peak coefficient is 0.45. When the rainstorm recurrence period is greater than 10a, the rain peak coefficient is 0.5.

According to the Wuhan rainstorm intensity formula and the rain peak coefficients in different recurrence periods, the rainfall intensity process lines and rainfall amounts of $5a$,$10a$,$20a$,$30a$,$50a$ and $100a$ can be calculated. Take 2 hours for example, and the rainfall and average rainfall intensity at different recurrence periods were shown in Table 2.

Tab.2 Rainfall and intensity with different rainfall recurrence

Return period（a）	rainfall intensity（mm）	Average rainfall intensity（mm/min）
5	75.02	0.625225349
10	102.10	0.8508956
20	117.16	0.976354424
30	125.96	1.049743131
50	137.06	1.142201968
100	166.59	1.388268252

The rainfall line in different recurrence periods is shown in Figure 8. As can be seen from the figure, the peak value of rainfall intensity usually occurs in about 60 minutes, and the maximum value of rainfall intensity in 5a recurrence is about 3.79 mm/min. With the increase of recurrence period, the peak value also increases continuously. The maximum value of rainfall intensity once in 100 years is about 7.57mm/min.

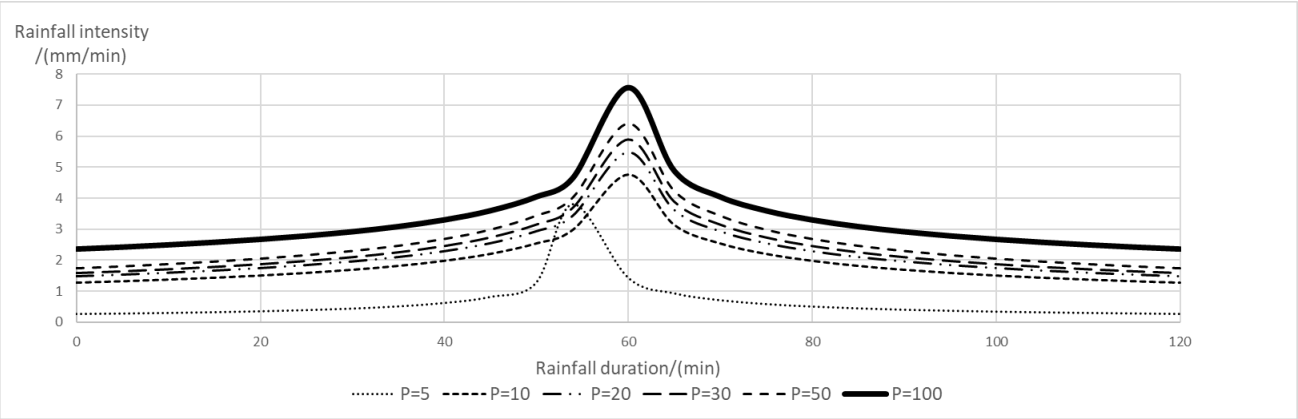


Figure 8. Rainfall process lines at different recurrence stages

According to the SCS runoff model, the land types in the study area are divided into four types: urban land, road land, grassland and lake. The boundary of different land types in the study area are sketched by CAD. And the areas of different land types are classified and counted. Different type's area and value of CN are shown in Table 3.

Tab.3 Statistical data of different land types

Catchment area	Land types	Area occupied	CN
North area	Urban land	0.32	81
	Street land	0.22	85
	Grass land	0.13	58
	Lake	0.11	98
	Total	0.78	
South area	Urban land	0.15	81
	Street land	0.10	85
	Grass land	0.08	58
	Total	0.33	

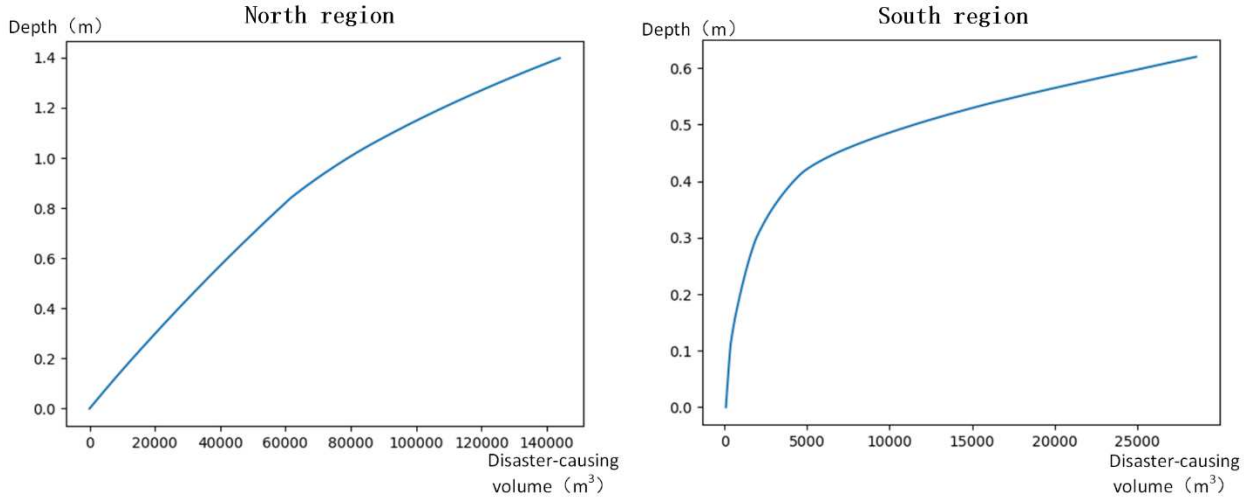
204

205 **3.2.2 Drainage information**

206 Because the study area is a small, the pumping and drainage capacity of the pumping station is not considered and
207 only take pip drainage into consider. According to the design standard of Wuhan drainage and waterlogging prevention
208 system, the design standard of Wuhan urban drainage pipe network is "once a year", and the drainage capacity is 36 mm/h.

209 **3.2.3 Submergence depth calculation**

210 On the basis of high-precision DEM data and urban waterlogging disaster model, the relation curve between disaster-
211 causing volume and inundation depth is calculated as shown in Figure 9. It can be seen that when the disaster-causing
212 volume is increasing, the submergence depth is increasing but the growth rate is gradually slowing down. This phenomenon
213 is related to the topographic characteristics of the study area. There are several areas that are prone to flooding all the year
214 around. At these place, with the continuous increase of the disaster-causing volume, the growth rate of the submerged area
215 is far less than that of the disaster-causing volume, as well as with the continuous expansion of the submerged area, the
216 growth rate of the submerged depth also slowed down.



217

218 **Figure 9. Relationship between the amount causing waterlogging and depth**

219 **3.3 Geographic feature data**

3.3.1 Spatial data preparation

The spatial data needed in the model mainly includes elevation data, building vector data and texture mapping. The elevation data and building vector data is obtained by manual field measurement. The texture mapping is obtained by camera. Part of the data is shown in Figure 10.

Figure 10. Part of the spatial data

3.3.2 Spatial data preparation

3D scene modeling is carried out according to the acquired spatial data, and the scene effect is shown in Figure 11.

Figure 11. 3D scene simulation of the ZUEL campus

3.4 Waterlogging disaster simulation

The urban waterlogging disaster simulation of different rainfall conditions is made on the 3D DEM model. And the results are shown in Table 4, which are the rainstorm waterlogging simulations of the return period of 5, 10, 20, 30, 50 and 100 years with 2 hours' rainfall duration.

Tab. 4 The rainstorm waterlogging simulations of different return periods

Catchment area	Return period（a）	Disaster amount（m^3）	Submergence depth（m）
North area	5	20772.5598	0
	10	41894.32683	0
	20	53636.92625	0.10
	30	60505.94465	0.17
	50	69159.91425	0.28
	100	92191.36053	0.46

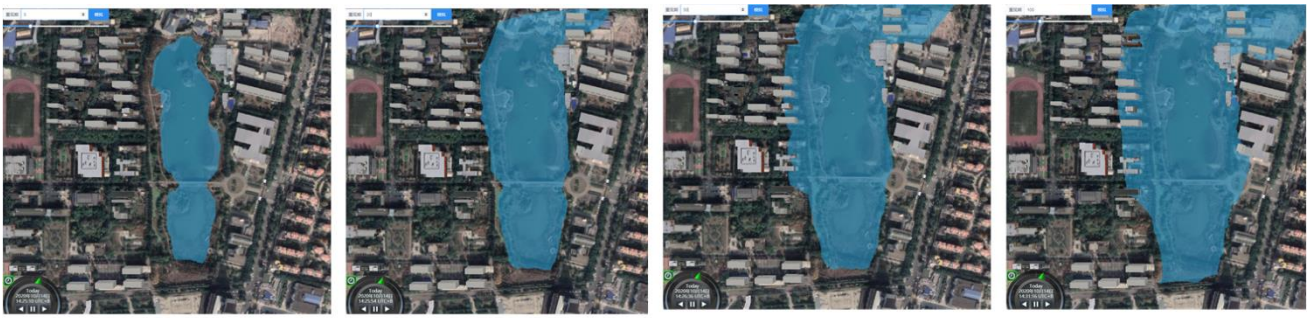
South area	5	659.2633906	0.20
	10	9594.218553	0.53
	20	14561.81857	0.57
	30	17467.74055	0.60
	50	21128.81822	0.62
	100	30872.45303	0.68

Figures 12 and 13 show the waterlogging scenarios of the north and south catchment area of the ZUEL campus by using the 3D visualization technology. The analysis is based on the results of 3D simulation and calculation.

When the rainfall return period is less than 20 years, the lake in north catchment area has good storage capacity which can protect the area from waterlogging disaster. But when the return period increases to 20 years, the waterlogging area takes the lake as the center and spreads to the surrounding area. Waterlogging begins to occur in the area. With the increase of years of return period, the waterlogging area increase rapidly while the submergence depth is low, which cause very little damage.

In the south catchment area, there is a local low topography, which leads to the waterlogging disaster even the rainfall period is 5 years. And the waterlogging area is relatively concentrated and small.

With the increase of years of return period, the increase of waterlogging area is not obvious but the submergence depth increases greatly. In the 100-year disaster simulation, the disaster situation in the south area is more serious than that in the north area. The simulation results are basically consistent with the waterlogging disaster caused by the 100-year- recurrence heavy rain in Wuhan in 2016.



(a) simulation in 5-year period of recurring rainfall (b) simulation in 20-year period of recurring rainfall (c) simulation in 50-year period of recurring rainfall (d) simulation in 100-year period of recurring rainfall

Figure 12. The waterlogging scenarios of the north catchment area of the ZUEL campus

(a) simulation in 5-year period of recurring rainfall (b) simulation in 20-year period of recurring rainfall (c) simulation in 50-year period of recurring rainfall (d) simulation in 100-year period of recurring rainfall

Figure 13. The waterlogging scenarios of the south catchment area of the ZUEL campus

4. Conclusions

Based on the previous studies and high-precision terrain data, the 3D DEM model is built in this paper to simulate the urban waterlogging disasters under different recurrence stages of rainfall scenarios. The region survey is focused on the campus of Zhongnan University of Economics and Law. The main conclusions are as follows:

- The model can effectively improve the simulation accuracy of waterlogging disaster. It can help to locate the disaster area accurately, and directly display the submergence range and depth of waterlogging disaster by using the 3D visualization technology. With the improvement of computer performance and the accuracy of measuring equipment, the research on urban waterlogging disaster tends to small regions. The study in this paper can provide an idea and method for the research on urban waterlogging disaster.
- The basis of waterlogging disaster simulation in this paper is to use the watershed extraction method to delimit the Sub-catchment area according to the high-precision DEM model of urban topography and geomorphology. The results are consistent with the actual terrain, which shows that the watershed extraction method is more suitable for waterlogging simulation in a small area then Manual Partition, Tyson Polygon Partition or Drainage Network Partition.
- The urban waterlogging disaster simulate model is built with in combination with the rainstorm intensity formula and SCS model of runoff simulation. The urban drainage network is simplified in this model, which can make the simulation calculation much easier but not affect the reliability of the results. This feature makes this model more suitable for waterlogging disaster simulation in urban areas without enough pipe network data.
- The waterlogging simulate method provide in this paper is easy to extend to other areas such as reservoir, tailings pond.

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Figures

Figure 1

The condition of waterlogging in 2016

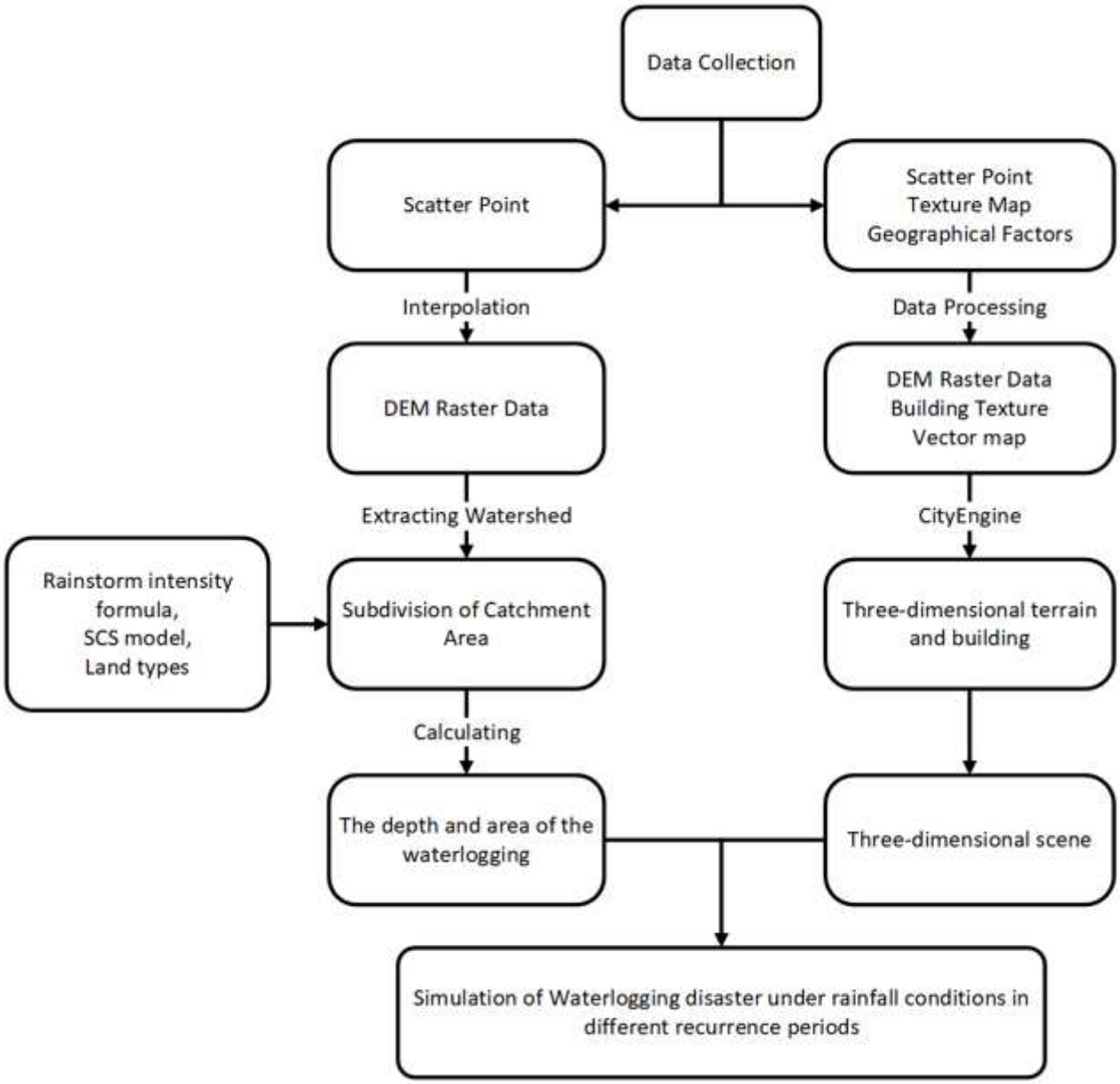

Figure 2

Framework of waterlogging simulation

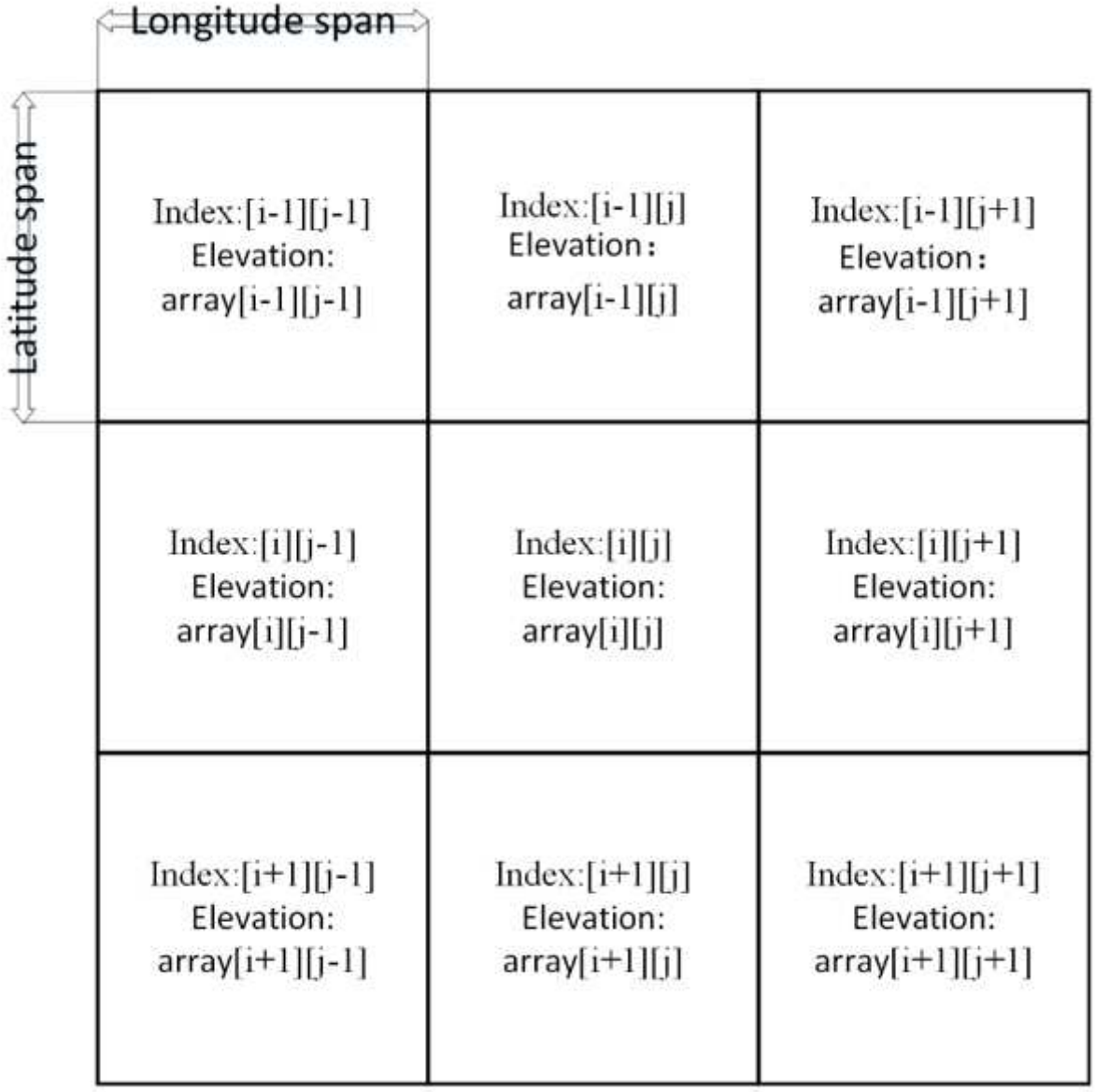

Figure 3

Principle of grid data

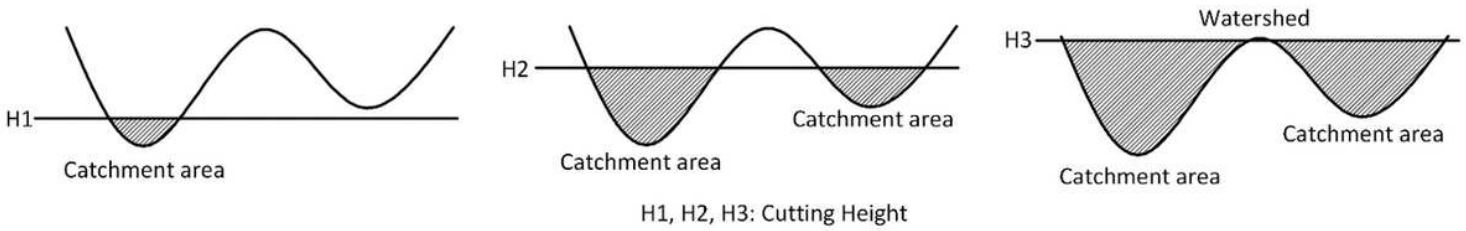

Figure 4

Principle of extracting watershed

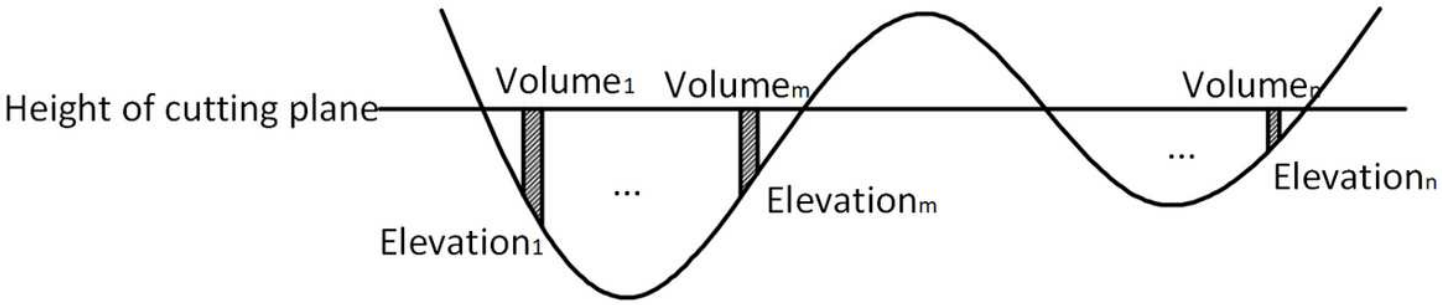

Figure 5

Principle of calculating the volume of DEM data

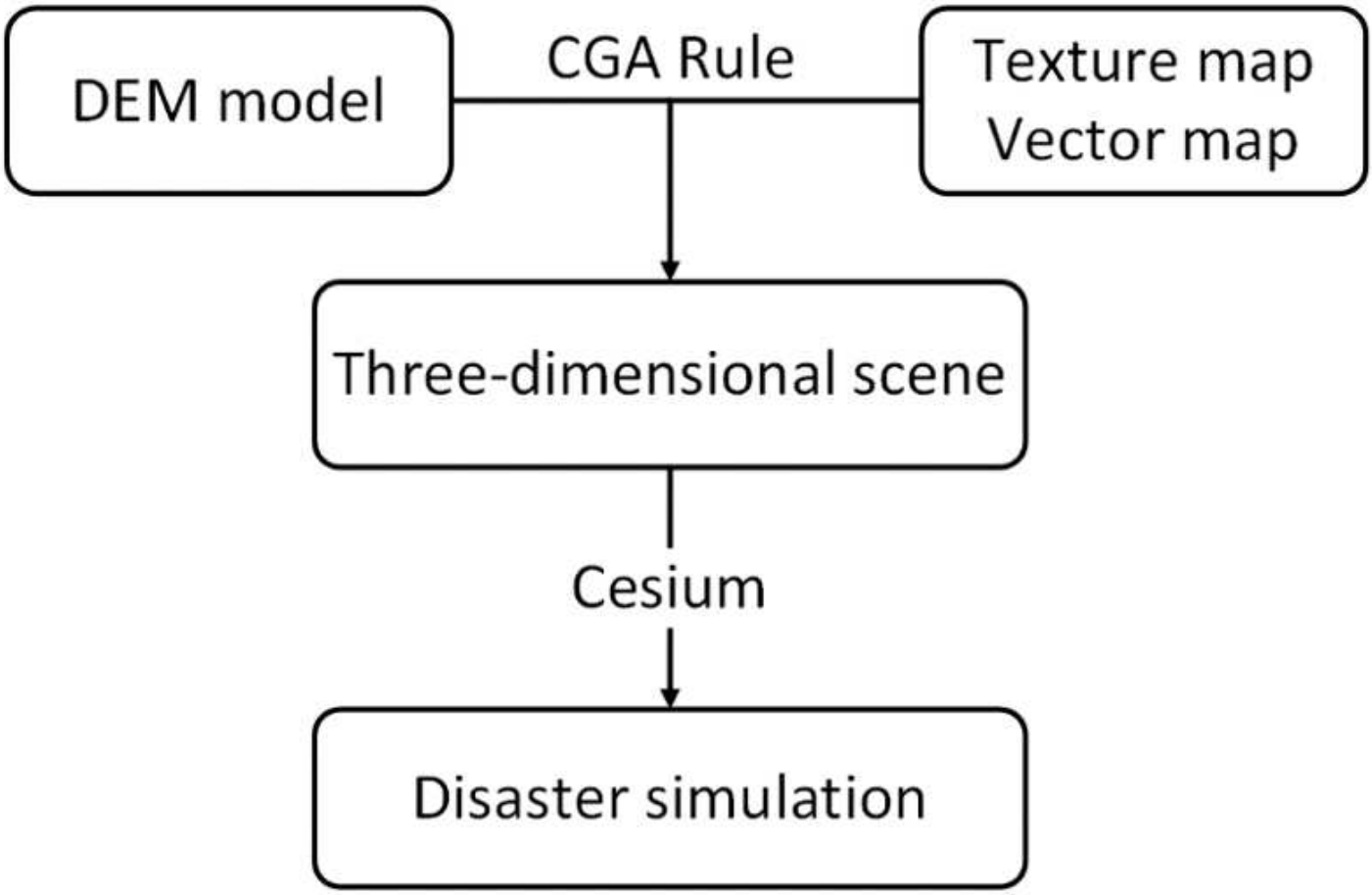

Figure 6

Framework of 3-dim visualization

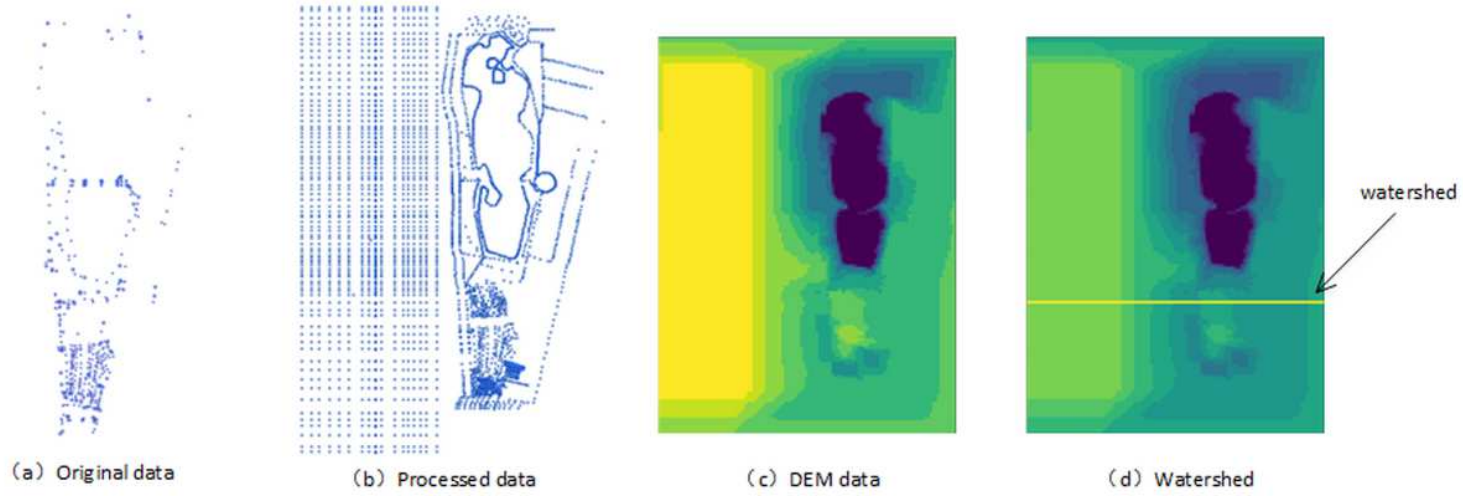

Figure 7

Results of processing the DEM data

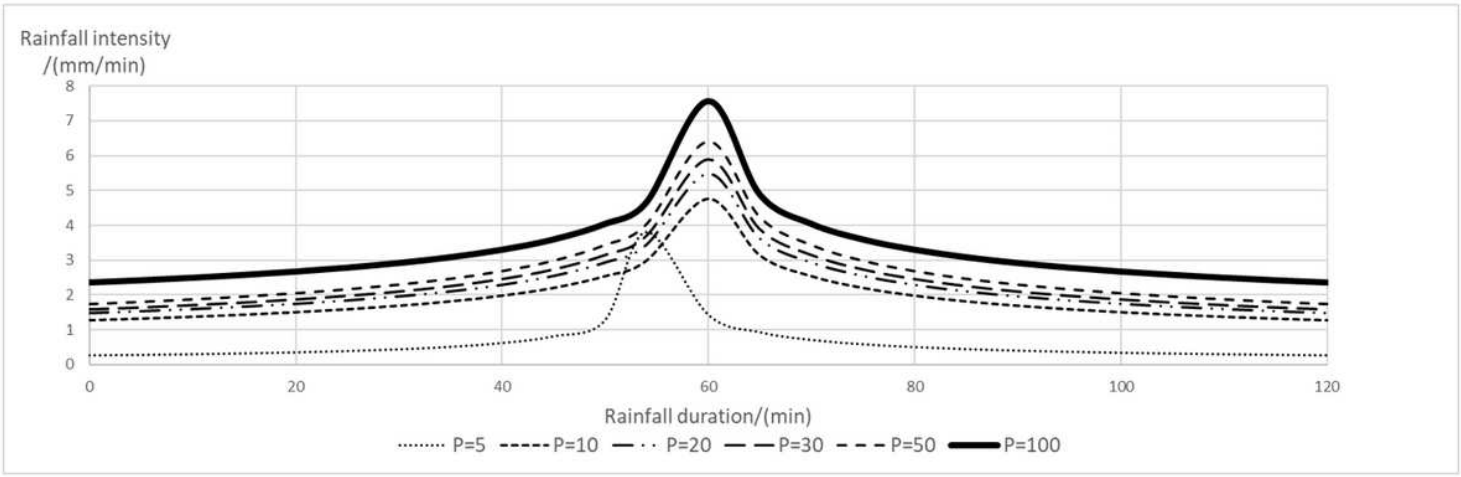

Figure 8

Rainfall process lines at different recurrence stages

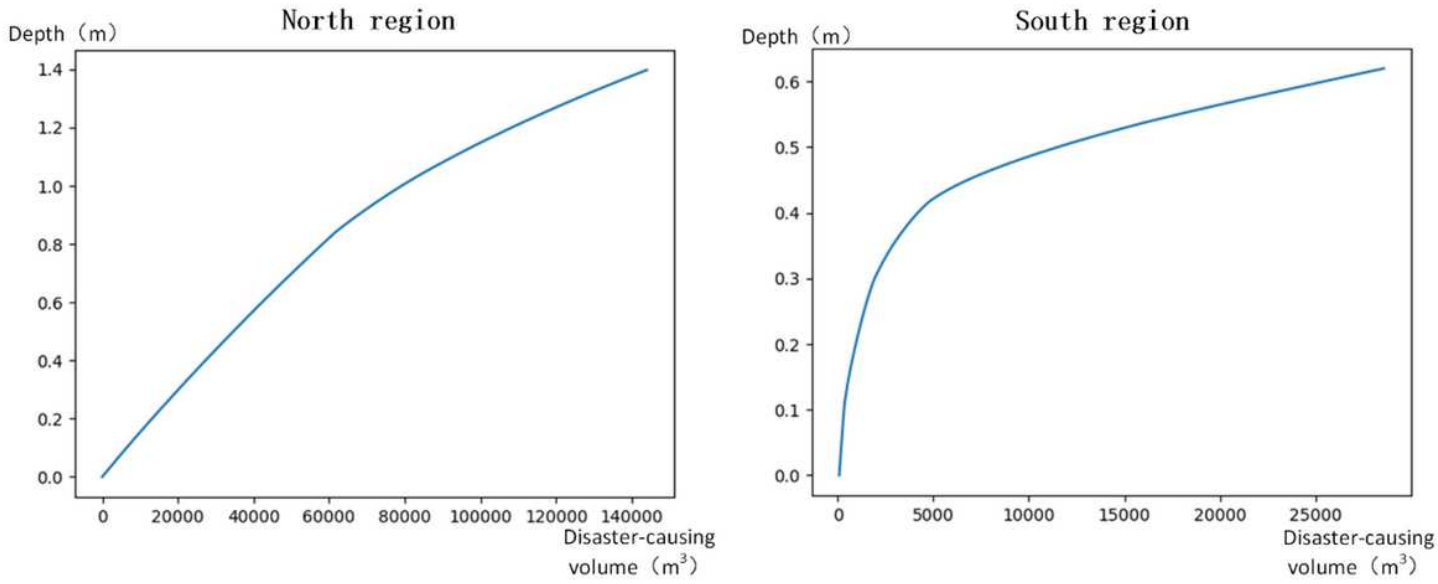

Figure 9

Relationship between the amount causing waterlogging and depth

Figure 10

Part of the spatial data

(a) simulation in 5-year period of recurring rainfall

(b) simulation in 20-year period of recurring rainfall

(c) simulation in 50-year period of recurring rainfall

(d) simulation in 100-year period of recurring rainfall

Figure 12

The waterlogging scenarios of the north catchment area of the ZUEL campus

(a) simulation in 5-year period of recurring rainfall (b) simulation in 20-year period of recurring rainfall (c) simulation in 50-year period of recurring rainfall (d) simulation in 100-year period of recurring rainfall

Figure 13

The waterlogging scenarios of the south catchment area of the ZUEL campus