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Analysis of water accumulation in urban street based on DEM generated from LiDAR data

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ABSTRACT

Aiming at the problem of submergence analysis in microscale scene of urban street, this paper takes an inundate area in Zhengzhou city as an example, the high-precision digital elevation model (DEM) of urban street inundate area is constructed from light detection and ranging (LiDAR) for land vehicles, and the overflow quantity of the waterlogged point is stimulated by the storm water model in Zhengzhou. The submerged area is computed by seed spread algorithm, and the submerged depth distribution is acquired by using the method of dichotomy to realize rapid approximation between submerged water level and overflow quantity. The application of the example shows that the stimulation results of urban storm water model can be quickly and accurately converted to corresponding submerged features by the suggested submergence analysis methods, which are based on the high-precision DEM constructed from LiDAR data. The submergence analysis methods satisfy computational efficiency and precision, which are suitable for water accumulation stimulation in inundate area of urban street.

Keywords: Submergence analysis; Vehicle-borne LiDAR; High-precision DEM; Storm water model; Urban water accumulation

1. Introduction

In recent years, due to the influence of the global climate extremist trend and the rapid urbanization process, the frequency, magnitude, and loss of heavy rains are ever increasing. On the one hand, impervious surface coverage in urban land use is significantly augmented, resulting in accelerated confluence process and increased runoff, the low-lying area is more prone to submerged [1]. On the other hand, the regulatory, prevention, and response capacity of municipal administration departments, as well as the standard and facilities construction of drainage cannot keep up with the rapid development of urbanization, and thus it is easy to cause urban waterlogging floods once heavy rainfall is encountered. How to quickly and accurately acquire the urban terrain information and analyze the submerged characteristics, and timely develop urban disaster prevention and mitigation measures is an important subject of urban flood control works.

The urban drainage calculation methods commonly used by municipal and water conservancy departments, such as rational formula, isochrones, and kinematic wave are mainly applicable to the planning and design of pipeline drainage system in urban district, which cannot meet the overload analysis of drainage system and the simulation calculation of ground flooded process [2–4]. In recent years, based on the digital elevation model (DEM), the hydrodynamic and hydrological model has been a focal point in the study of urban flood control and waterlogged elimination [5]. Urban rainfall-runoff model, which is represented by storm water management model (SWMM), is used to simulate the water cycle of infiltration, evaporation, surface runoff, subsurface runoff, and drainage system output in the urban area during

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rainstorm. The amount of water in the surface is represented as the overflow quantity from the waterlogging point, which has been verified and recognized in research and application practice [6–8]. SWMM is a distributed hydrological model, which divides the urban area into spatial grids [9]. However, the model does not directly construct the spatiotemporal correspondence between overflow and flooding area and depth, and it cannot realize the response between the model calculation result and the submerged characteristics.

Liu and Liu [10] and Ge et al. [11] discussed two different cases for flood submerge, namely "non-source flood" and" source flood," respectively, based on DEM. The non-source flood case only takes the elevation value below the given water level as the condition of the ground grid unit entering the submerged area, which ignores whether the flow can reach the area. The source flood case firstly analyzes the area that the flow from a certain point can reach at a given water level, thus the submerged range is limited to the connected area, which is consistent with the natural flow characteristics of water. The source flood case is widely used in research about flood burst and overflow submergence caused by local rainstorm, but there is still debate about its algorithm design [12]. For example, the recursive algorithm is simple and straightforward, but its computational efficiency and stability are difficult to guarantee when the recursive depth is too deep [13]. In addition, the precision of the submergence calculation is mainly determined by spatial resolution of the DEM [14]. The low-resolution DEM is applicable to the submerged calculation of macroscale area such as basin, but it cannot meet the accuracy requirement of the submerged calculation in microscale area of the street area in flat plain city, such as Zhengzhou.

In this study, the high-precision DEM of urban street inundate area is constructed from light detection and ranging (LiDAR) for land vehicles, and the overflow quantity of the waterlogged point is stimulated by the storm water model in Zhengzhou. Seed spread algorithm is used to submerged area calculation, and the submerged depth distribution is acquired by using the method of dichotomy, which are proved to be suitable and precise for water accumulation stimulation in inundate area of urban street by the application of the example

2. Methods

2.1. Construction method of high precision DEM based on LiDAR for land vehicles

LiDAR for land vehicles is able to perform real-time, accurate, automatic, on-demand scans on both sides of the motion trajectory to generate images and point cloud data. The Global Navigation Satellite System/Inertial Navigation System (GNSS/INS) integrated navigation system ensures the accuracy and reliability of the output of mobile platform motion trajectory [15], the high-precision GNSS positioning results control the system drift of the INS and make continuous error updates, and at the same time INS reduces the ambiguity search range and time of GNSS when the signal is out of lock [16,17].

The street submerged area in plain city is taken as the research object, which is urban microscale area with flat surface and complex ground object, including culverts, viaducts, and other intricate scenes. The high-precision DEM of urban street submerged area is constructed based on the 3D laser scanning point cloud data collected from LiDAR for land vehicles, and the construction process is shown in

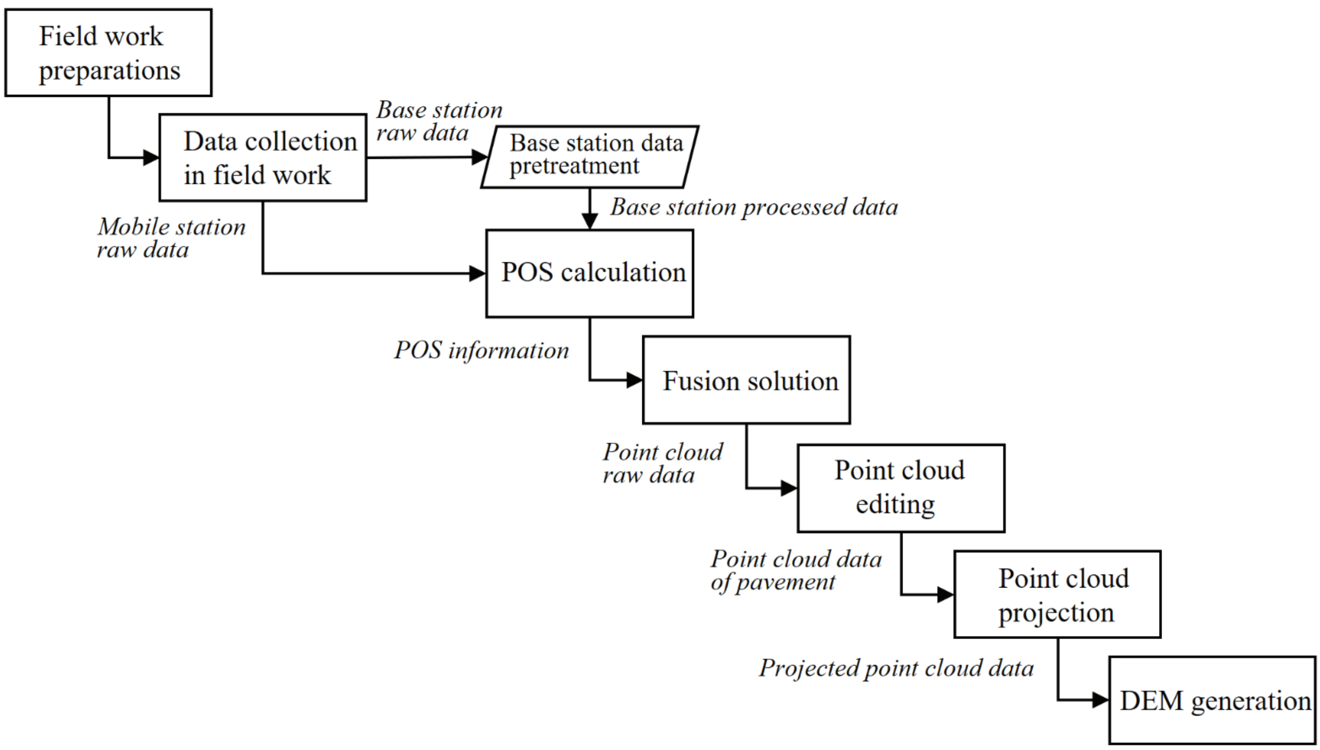

Fig. 1. Processes of DEM construction from LiDAR for land vehicles.

Fig. 1. Error points and non-stacked object points (such as vegetation points) should be removed from the point cloud data firstly, and then these filtered point clouds are projected for grid DEM generation. The general road surface should be relatively smooth; however, the generated DEM will appear a small area of depression or convex due to some point clouds are blocked. In this study, the fill tool in the hydrological analysis module of ArcGIS version 10.2 is applied to smooth the pavement DEM. If the main characteristic line of the pavement after the above process is still not obvious, characteristic line interpolation is conducted to obtain smooth grid DEM data with distinct characteristics, on the basis of the road characteristic line diagram (.dwg format) extracted by point cloud.

The DEM construction processes (Fig. 1) are as follows:

2.1.1. Field work preparations

According to the requirements for accuracy and efficiency of data acquisition, combined with the actual situation of the area for data collection, the field surveying planning is drawn up, including scan scope and route planning, staff and task arrangements, and so on.; after inspection, the device is installed and debugged; erecting the base stations and setting related acquisition parameters.

2.1.2. Data collection in field work

According to the field surveying planning, the acquisition device and supporting control software of integrated mobile 3D measurement system of LiDAR are applied for data collection in surveying operation area.

2.1.3. Positioning and Orientation System calculation

First, the base station data and mobile station data should be converted into the data format supported by the fusion software (Internal Explorer version 8.50) by pretreatment. Then all available data of GNSS and INS are calculated by the fusion software, and high-precision combined navigation information (Positioning and Orientation System [POS] information) including location, speed, and attitude are acquired.

2.1.4. Fusion solution

The raw data collected from LiDAR are fused with the POS information to generate the point cloud data.

2.1.5. Point cloud editing

The error points and non-stacked object points (such as vegetation points) should be removed from the point cloud data to ensure the accuracy of subsequent processing. If the noise point is less, it can be deleted manually. On the contrary, the point cloud should be classified to extract the ground point.

2.1.6. Point cloud projection

Due to the scanning point cloud is high-density and each DEM data grid corresponds to only one elevation value, it is necessary to rarefy data and project the edited point cloud to the grid. After the projection grid size is determined, the elevation value in the grid can be set by projection mode of the average, the highest point, or the lowest point according to the demand.

2.1.7. DEM generation

The pavement DEM data are generated by the build tool of the measurement system, and the DEM grid size is consistent with the projection grid size of point cloud. The generated DEM data are imported into ArcGIS for processing, including cutting, filling, smoothing, characteristic line interpolation, and so on, to obtain a smooth pavement DEM data with obvious characteristics.

2.2. Calculation method of water accumulation in urban roads

According to the case of source flood, the submerged area is computed by seed spread algorithm based on the high-precision DEM data of urban street submerged area. On the basis of the construction of the storm water model in Zhengzhou, the submerged depth distribution is acquired by using dichotomy to realize rapid approximation between submerged water level and overflow quantity.

2.2.1. Submerged area calculation

Based on the high precision DEM of urban street submerged area constructed from LiDAR for land vehicles, the submerged area under the given water level is calculated in the case of source flood. In this study, the seed spread algorithm based on eight-direction search is designed for the calculation of submerged area in the case of source flood.

In this study, the initial seed point position was determined by D8 (deterministic eight-node) algorithm, which is the most widely used single-flow-direction algorithm [18]. In a 3 × 3 DEM grids window, the center grid outflow water can flow to the surrounding eight grids and corresponds to eight directions divided by 45°. The elevation difference of each direction is calculated as $E = e_x – e_n$, where e_c is the elevation of central grid and e_n is the elevation of neighborhood grid. Then the elevation difference with distance weight is defined as D. In the horizontal and vertical direction, $D = E$. In the diagonal direction, $D = E/\sqrt{2}$. Then the flow starts from the center grid to the neighborhood grid with the maximum D value. The process of the D8 algorithm is shown in Fig. 2.

Each grid unit of DEM in urban street submerged area can be uniquely identified by its row and column number, assigning elevation values of DEM raster to a two-dimensional array named "demArr[][]" and creating a two-dimensional array of the same size named "Isflood[]" to hold the decision of whether the grid is flooded. The center grid in column J of Line I, along with eight adjacent grid DEM data is shown in Fig. 2.

During the confluence process, the water flows along one or more of the steepest paths in the DEM grid to the most low-lying area of the region, and at that point begins to spread to the periphery, which is the initial seed point of the seed spreading algorithm. The DEM data of urban street submerged area obtained from LiDAR for land vehicles are of high accuracy, and the D8 algorithm can meet the requirements of the flow analysis in urban street scene based on high-precision DEM data.

The seed spreading algorithm is realized with Java programming, and the algorithm flow and main code are as follows:

Algorithm main function is given as follows:

```
public void seedSpreading(int startRow,int startCol,double floodLevel)
```

1. Definition and initialization of variables.

```
int totalRows=demArr.length;        //total number of rows of DEM
int totalCols=demArr[0].length;     //total number of columns of DEM
isFlood=new boolean[totalRows][totalCols];      //flooded array
Stack myStack=new Stack(100);       //initial stack
```

2. Judging condition: The initial seed point is not crossed and its elevation is lower than the flood level.

```
if(startRow<totalRows && startCol<totalCols && DemArr[startRow][startCol]<floodLevel)
```

3. If the above judgment is true, then the point is added to the flooded stack.

```
DEMPoint point=new DEMPoint(startRow,startCol);
point.setFlood(true);               //set to flooded
myStack.push(point);                //the point is added to the flooded stack
```

4. Loop condition: Stack is not empty.

```
while (!myStack.isEmpty())
```

5. After entering the loop, the first element of the stack is got and ejected.

```
DEMPoint temPoint=myStack.peek();   //the first element of the stack is got
row=temPoint.getRow();
col=temPoint.getCol();
isFlood[row][col]=true;             //the element is set to flooded
myStack.pop();                      //the element is ejected from the stack
```

6. Adjacent elements of the element are traversed.

```
for(int i=row-1;i<=row+1;i++){
    for(int j=col-1;j<=col+1;j++){
```

7. Judgment condition: The adjacent element is not crossed and its elevation is lower than the flood level.

```
if(i<totalRows&&i>=0&&j>=0&&j<totalCols){
    if(isFlood[i][j]==false&&demArr[i][j]<floodLevel){
```

8. If the above judgment is true, then the point is added to the flooded stack.

```
temPoint=new DEMPoint(i, j);
myStack.push(temPoint);
```

2.2.2. Submerged depth calculation

A certain inundate area is regarded as reservoir, and there is a corresponding relationship between water level and storage capacity, that is, for a certain overflow quantity Q, there is corresponding storage capacity(volume of water accumulated) V and water level Z in the water accumulation area. According to the DEM grid size, the water accumulation area is divided into grids, the volume of water in each grid is calculated, then the volume of water in all the grids are added to the total volume V (Fig. 3).

The total volume of water accumulated in inundate area is calculated as follows:

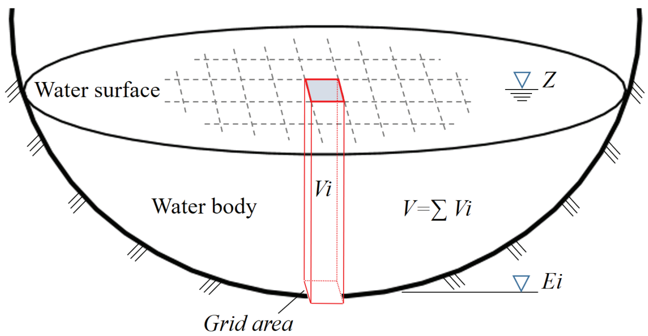

Fig. 3. Diagram of the calculation of water accumulation volume in inundate area.

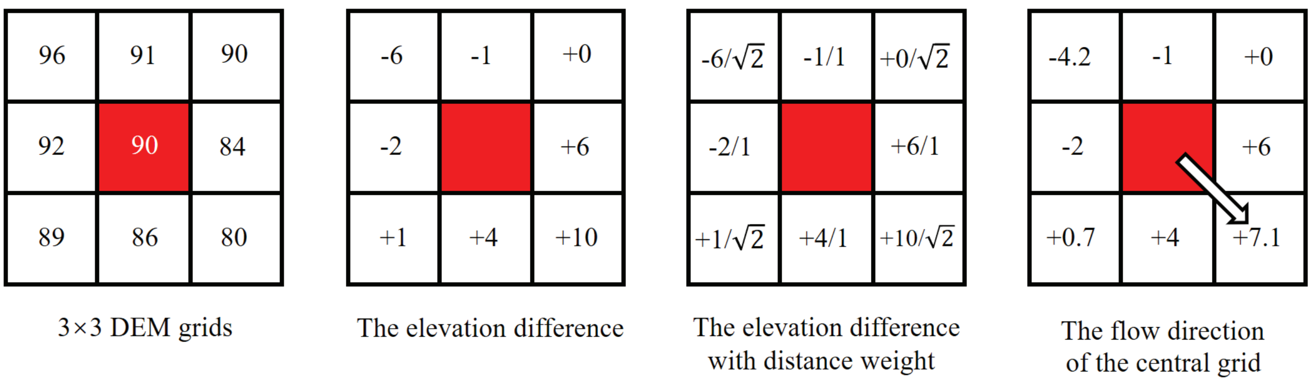

Fig. 2. The process of the D8 algorithm.

$$V = \sum_{i=1}^{m} V_i = gridArea \cdot \sum_{i=1}^{m} (Z - E_i) \quad (1)$$

where Z is a given water level value, E_i is the elevation value of ith DEM grid lower than Z, gridArea is the area of each DEM grid, and m is the number of grids.

Comparing the overflow quantity Q with volume of water accumulated V, the Z will be increased if $Q > V$; on the contrary, the Z will be reduced, thereby V keeps approaching Q. The Z obtained by approximating and satisfying the accuracy is the water level corresponding to a specific volume of water accumulated Q. Under the premise of the known overflow location P and overflow quantity Q, the corresponding submerged depth distribution can be obtained theoretically based on the high-precision DEM data; the key is how to achieve the fast approximation between the submerged water level and the overflow quantity.

In this study, the fast approximation calculation of submerged water level is realized by using the method of dichotomy. For a function $y = f(x)$ which is contiguous on the interval $[a, b]$ and $f(a) \cdot f(b) < 0$, the dichotomy means that by continuously dividing the interval of zero points of the function $f(x)$ into two, the two endpoints of the interval are gradually approximated to zero points, and then the approximate value of zero points is obtained. The objective function is built as follows:

$$f(Z) = Q - V(Z) \quad (2)$$

where Q is overflow quantity of the waterlogged point, which can be calculated by storm water model; $V(Z)$ is the volume of water accumulated at the specific water level Z.

The continuity of $V(Z)$ indicates that $f(Z)$ is continuous and $f(Z_{max}) \cdot f(Z_{min}) < 0$, wherein the Z_{max} and Z_{min} are, respectively, the upper and lower limits of the water level, corresponding to the highest and lowest elevation of DEM in the connected domain.

The implementation steps of dichotomy are as follows:

- Determine the interval $[Z_{min}, Z_{max}]$ and precision value ξ, verify that $f(Z_{max}) \cdot f(Z_{min}) < 0$;
- Find the midpoint Z of the interval $[Z_{min}, Z_{max}]$;

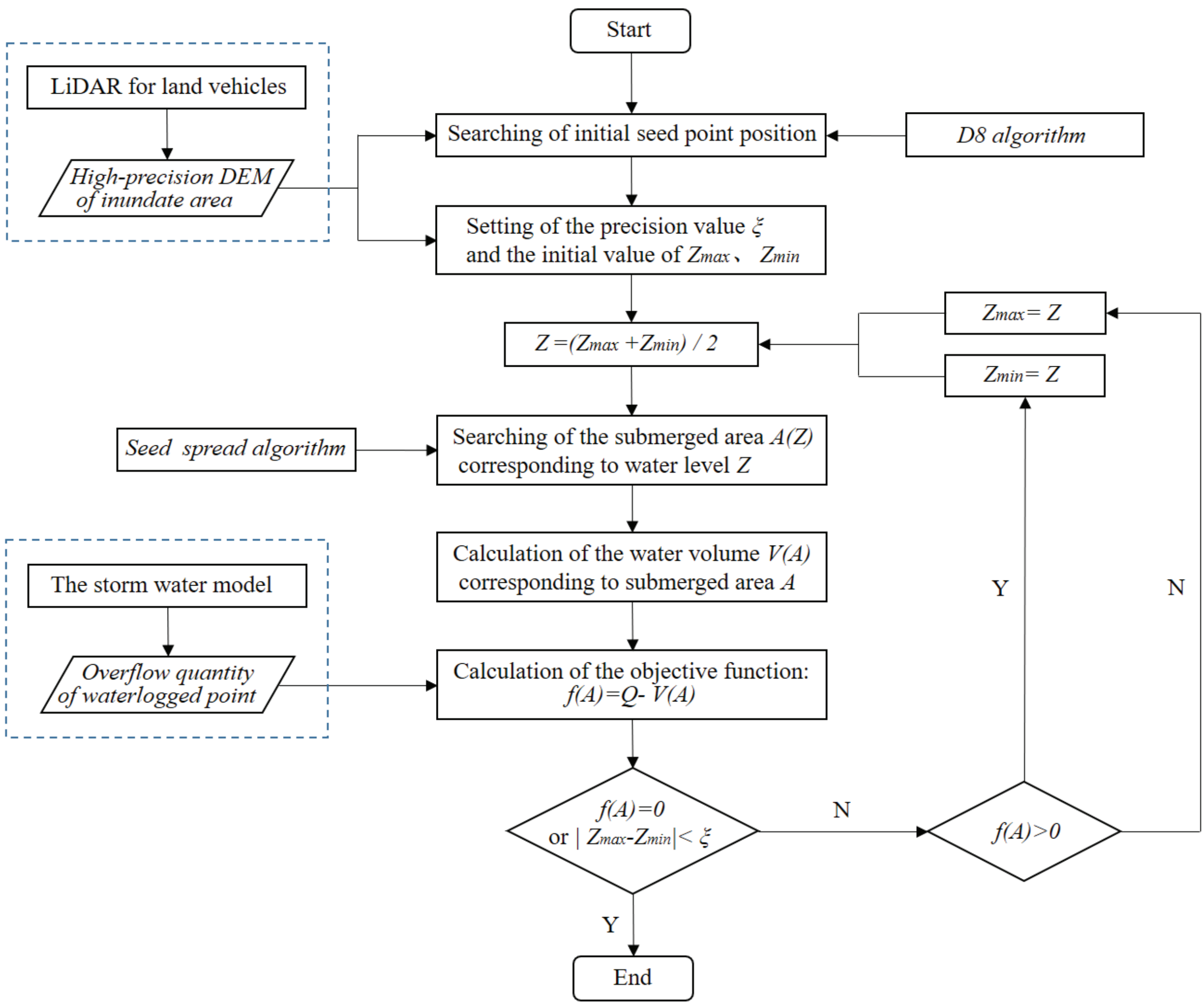

Fig. 4. Flow chart of the analysis of water accumulation in inundate area.

- Calculation of $f(Z)$: If $f(Z) = 0$, then Z is the zero point of the function; If $f(Z) < 0$, then $Z_{max}=Z$; If $f(Z) > 0$, then $Z_{min} = Z$;
- Determine whether the precision is achieved: If $|Z_{max}-Z_{min}| < \xi$, then calculation ends and the approximation of zero point Z of the function $f(Z)$ is obtained, otherwise steps (2)–(4) should be repeated.

The process of the analysis of water accumulation is shown in Fig. 4. The computed result of H is the flooded water level which corresponds to the overflow quantity Q in the urban street submerged area, and the water level is subtracted from the ground elevation of a position to get the submerged depth of the location; the $A(Z)$ calculated by seed spread algorithm at water level Z is the corresponding submerged area.

3. Results and discussion

3.1. Construction of high-precision DEM in inundate area

In this study, the case of the process of rainstorm and water accumulation in an urban street area located in a culvert under railway bridge in Zhengzhou is analyzed; the location of the studied waterlogged point is shown in Fig. 7. The mobile 3D laser scanning system of iScan is used to collect and process the point cloud data of the studied area; the main technical parameters of scanning device are shown in Table 1.

The point cloud data are obtained after POS calculation and fusion solution (Fig. 5(a)), and error points and non-stacked objects points should be removed from the point data by editing (Fig. 5(b)). Grid size is set to 0.1 m, and the point cloud data is projected by the means of average value for DEM generation (Fig. 5(c)). After cutting, fill, and characteristic line interpolation, the high-precision grid DEM data with obvious characteristic in urban street inundate area are obtained (Fig. 5(d)).The 3D display effect of DEM in ArcScene is shown in Fig. 6, and the display results have obvious characteristics of culvert, which are consistent with the actual terrain features of the study area.

3.2. Construction of the storm water model in Zhengzhou

The storm water model in Zhengzhou is established based on SWMM, the model construction process which includes drainage system generalization, sub-catchments partition, the calculation of slope and impervious surface coverage, and parameters setting. According to the actual situation of drainage division of Zhengzhou city, as well as the status quo and planning pipe network situation, the pipe network is generalized to 2,435 nodes (rainwater wells),

Fig. 6. 3D display of the generated DEM data.

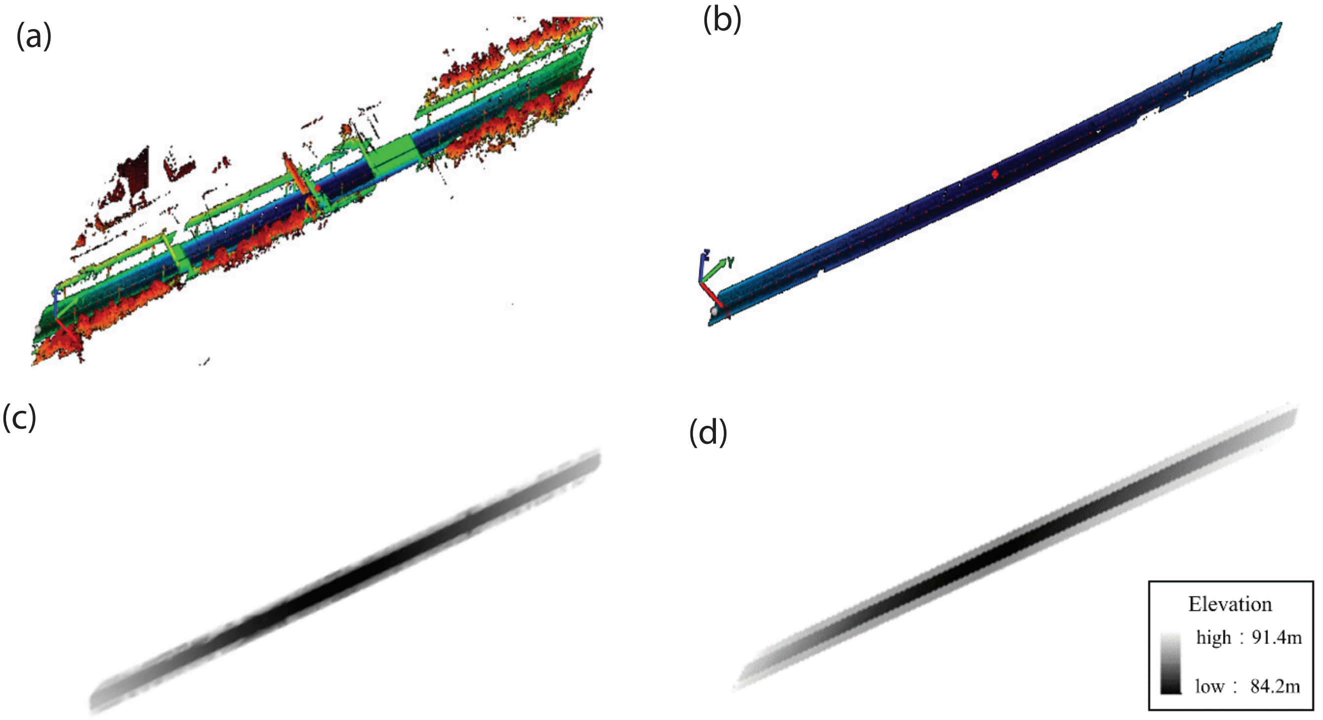

Fig. 5. Generation process of the DEM data in the studied inundate area: (a) point cloud row data, (b) point cloud edited data of pavement, (c) generated DEM data after projection, and (d) DEM edited data.

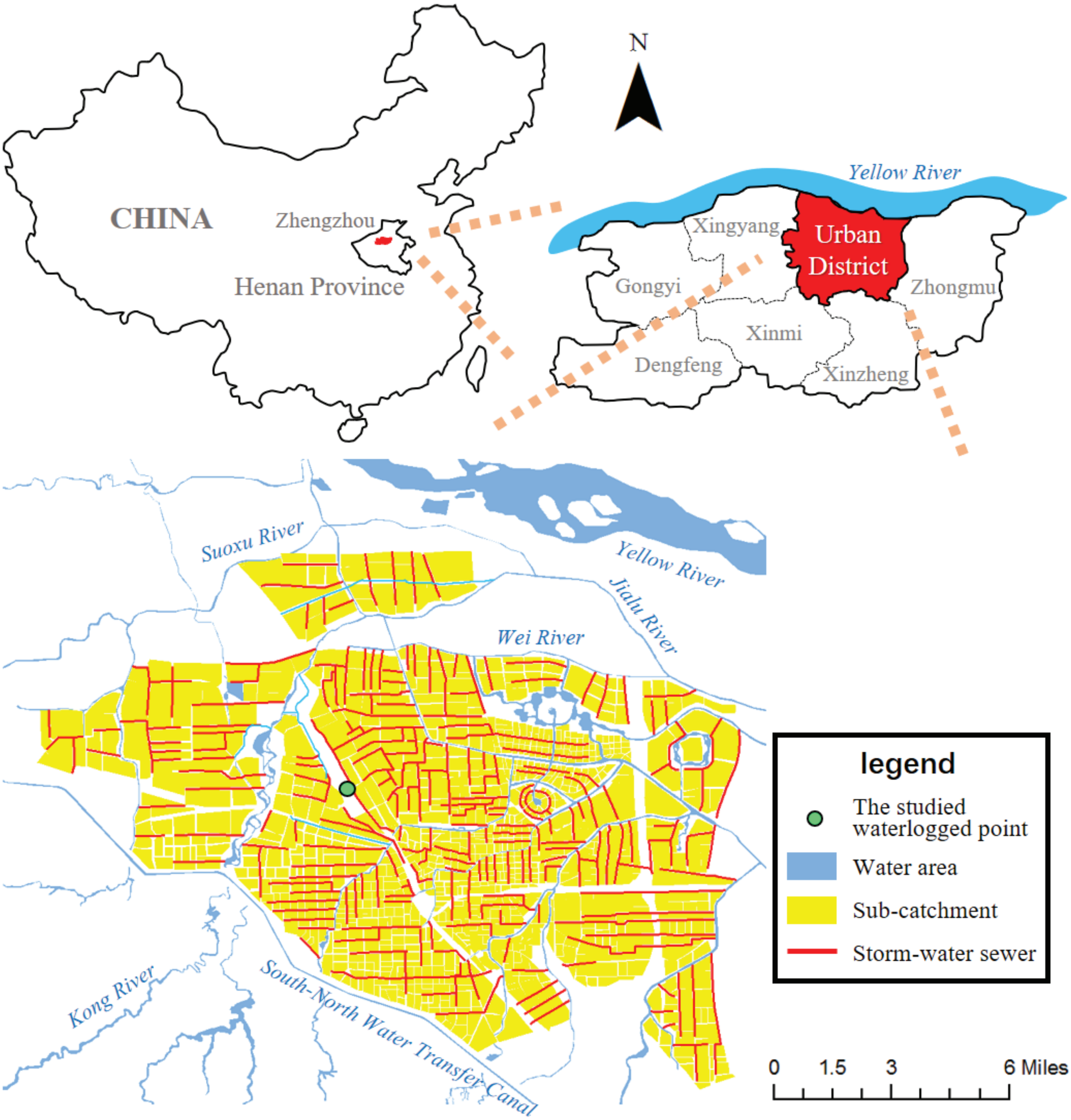

Fig. 7. General situation of Zhengzhou city and studied area. (Source: 'Zhengzhou city master plan map (2010–2020)' provided by the Water Resource Department of Henan Province.)

2 outlets, and 2,458 pipes (Fig. 7). The Zhengzhou urban area is divided into 3,324 sub-catchments by method combined ArcGIS automatic division with manual division; the total area is 595.34 km^2 and the average area is 0.18 km^2, and the surface of the study area belongs to the road impermeable ground. The raster surface slope tool in ArcGIS is used for slope calculation of DEM in the study area, and the zonal–zonal statistics tool in ArcGIS is applied to statistics analysis of average slope of each sub-catchment area, and the impervious surface coverage of each sub-catchment is calculated by the results of land use classification based on remote sensing images processed by ENVI version 5.1.

The measured rainfall data about several short-duration rainstorms, along with the corresponding flood data of river outlet in Zhengzhou, are selected as input for model parameters calibration. According to the literature data and technical manuals, and considering the actual situation of sub-catchments, the initial values of empirical parameters are set up [19]. Then, parameters calibration executes by model running; calibration results are shown in Table 2. For the

Table 1
The main technical parameters of the scanning device of iScan

Parameter	Value
Scanner number	2
Scan frequency	2 × 200 Hz
Maximum laser frequency	1 million points/s
Maximum measurement range	650 m
Reflectivity	90%
Scanning angle range	360°
Scanning angle resolution	0.001°
Panoramic resolution	75 million pixels
Measuring accuracy	5 cm
LiDAR data point density (when the horizontal scanning distance is 10 m)	9,236 points/m^2
Time of data collection	August 2008

Table 2
The calibration results of model parameters

Parameter		Calibration results
Manning coefficient	Pipe	0.014
	Channel	0.03
	Permeable area	0.18
	Unpermeable area	0.021
Depression storage	Permeable area	6.8 mm
	Unpermeable area	3.5 mm
Horton formula	Maximum infiltration rate	76.2 mm/h
	Minimum infiltration rate	3.6 mm/h
	Attenuation coefficient	3h^{-1}

unpermeable area, net rain amount is obtained by deduction of the initial abstraction from rainfall process (to the depression storage mainly), and runoff yields under saturated storage. For the permeable area, the Horton model is used for the infiltration and surface flow simulation. The non-linear reservoir method is applied to urban surface flow confluence calculation, and the kinematic wave model is adopted to pipe flow confluence. After adjusting the parameters, the Nash–Sutcliffe coefficients between the simulated flow process and the measured flow process are all greater than 0.8, which indicates that the calculated results coincide with that measured actually. In summary, the model calculation results are reasonable and reliable, and the storm water model in Zhengzhou is applicable to the simulation of storm flood progress of the region.

3.3. Flood submergence calculation and result validation

On the basis of high-precision DEM, the relation curves of water volume and submerged features of the studied inundate area are obtained by the above methods (Fig. 9). As can be seen from Fig. 8, the increasing trend of the maximum water depth is fast firstly and then slow with the raise of the water volume, this is due to the water depth converted from the equivalent amount of water volume is getting smaller with the water area gradually increasing. Simultaneously, the water area enlargement rate appears the change of fast-slow-fast with the increase of water volume, which is related to the topographic characteristics of the culvert under the railway bridge in studied inundate area. The elevation of the motorway in the middle of the road in culvert is lower than non-motor vehicle lanes on both sides, thereby the section shape of culvert in studied inundate area is characterized by low, middle, and high sides, and the maximum elevation difference is 3 m. Therefore, the constantly accumulating water would overflow from the motorway to the non-motor vehicle lanes on both sides, and the growth rate of the submerged area increases significantly when the maximum depth of water accumulated exceeds 3 m, which is consistent with the slope variation of the curve of the water area and water volume in Fig. 8. In summary, the high-precision DEM can accurately reflect the topography of the micro-scale area in urban street, and the water accumulation features calculated by the suggested methods are consistent with the actual submerged condition of the studied inundated area.

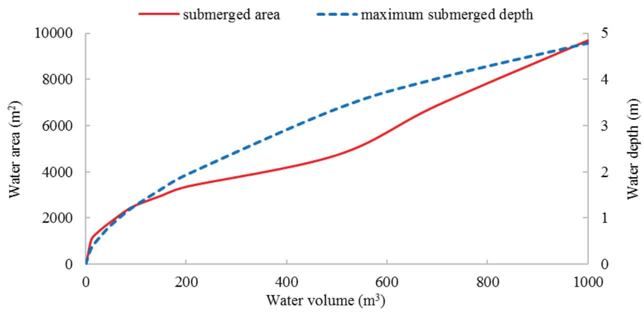

Fig. 8. The relation curves of water volume and submerged features of the studied inundate area.

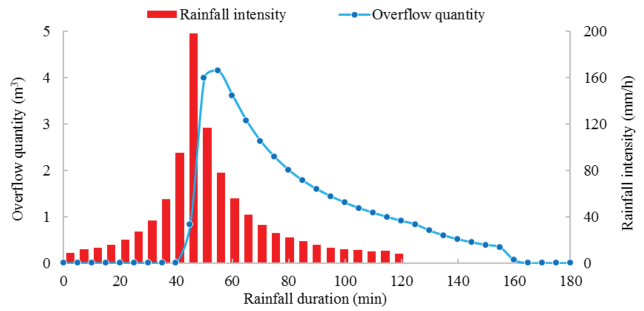

Fig. 9. Rainfall process and stimulation of overflow quantity.

An observed rainstorm process is further converted into the corresponding change sequences of submergence features in studied inundate area. To begin with, the overflow quantity sequence of waterlogged point is stimulated by the storm water model in Zhengzhou with the model input for an observed time series of rainfall intensity (Fig. 9). Next, the suggested submergence analysis method is used to obtain the relation curves between sequences of submerged depth and area with rainstorm process (Fig. 10). Finally, by comparing the calculated result with the variation data of the submerged depth measured by auto water gauge at the waterlogged point during the same rainstorm, the Nash–Sutcliffe coefficient is 0.91, the RMSE is 0.07, and the BIAS is 10.6%, which indicates that the calculation results have high accuracy.

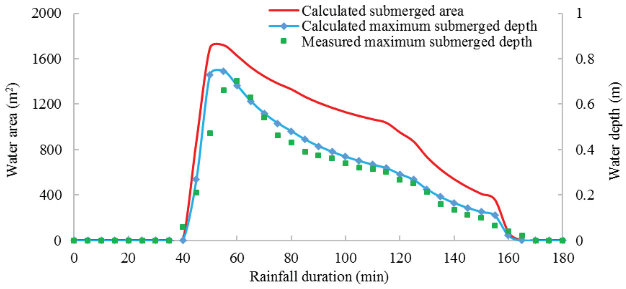

Fig. 10. Comparison between the calculated results and the measured results of submerged information.

Therefore, the suggested submergence analysis method is applicable to the flooding features calculation in inundate area of urban street.

4. Summary and conclusions

LiDAR for land vehicles is applied to build high-precision DEM in inundate area of urban street in this study, which lays the data foundation for submergence analysis. Urban street area belongs to the micro-scale scene with flat surface and complex ground object, which has high accuracy requirements for DEM data. The mobile mapping system for land vehicles is one of the most advanced technologies in modern surveying and mapping. With the help of flexible mobile platform, combined with advantage complement and efficient collaborative navigation module and sensor for data acquisition, this system can realize real-time, accurate, automatic, and on-demand collection of massive spatial geography data, which is applicable to urban street scene.

On the basis of high-precision DEM in inundate area, the overflow quantity of the waterlogged point is calculated by the storm water model in Zhengzhou, the submerged area is computed by seed spread algorithm, and the submerged depth distribution is acquired by using the method of dichotomy to realize rapid approximation between submerged water level and overflow quantity. The seed spread algorithm can search the submerged area under given water level based on high-precision DEM data accurately and efficiently, which has illustrious improvement in recursion depth, computational efficiency and stability, and system resource savings compared with the recursive algorithm. The dichotomy is the most intuitive method for solving nonlinear equations, which is characterized by simple computation and reliable results.

The application of the example shows that the stimulation results of urban storm water model can be quickly and accurately converted to corresponding submerged features by the suggested submergence analysis methods, which based on the high-precision DEM constructed from LiDAR for land vehicles. The submergence analysis methods satisfy computational efficiency and precision, which are suitable for water accumulation stimulation in inundate area of urban street. It is necessary to further study the rapid construction of 3D scene and dynamic visualization of the submerged process in urban inundate area, as well as the integration with the urban rainstorm decision management system, to improve the level of early warning, monitoring, management, and control about the urban rainstorm and waterlogging.

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