Intelligent Planning of Rain Water Drainage System in New Urban Areas Considering the Planning of Road Network

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Abstract

In the context of global urbanization, the waterlogging occurs more frequently. The cause of waterlogging is that the traditional planning of urban rainwater network was backward, which led the rainwater on the ground cannot be collected and drained timely. This study aims to build an intelligent rainwater pipe network planning system based on the SWMM and GIS components. Firstly, the SWMM model was packaged into a .NET managed dynamic library through a software interoperability model to implement the seamless integration with GIS software components. Secondly, on basis of the vertical design elevation and the planning road network data of the city, a grid DEM that in view of road network was built. And the hydrological parameters were automatically extracted by using GIS spatial analysis based on the planned land type and the torrential rain model of the study area. Finally, with the geometric network analysis function of GIS and the rain-flood simulation function of SWMM, the intelligent layout and optimization of rainwater drainage network were realized. And based on the weight model, the urban rainwater pipe network was optimized. The experimental results demonstrated that our method is more efficient than the traditional method. Specifically: (1) the prediction accuracy of rainwater pipe network is improved; (2) the nodes that may overflow are adjusted to the best state, which reduces the risk of urban waterlogging. These findings indicate the optimized pipelines are more scientific and economical in the layout scheme, the selection of outlets and the calculation of pipe force.

Key Words: Rainwater Drainage Network, GIS, SWMM, Hydrological Parameters, Intelligent Planning

1. Introduction

With the rapid expansion of the city, great changes have taken in the urban landscape, the most pervasive sign is considered to being the transformation from natural land to imperviousness [1,2]. These changes can lead to an increase in the impermeable surface of the city, which can give rise to urban waterlogging. The waterlogging caused by a rainstorm has long plagued many cities in China and has caused various levels of damage to urban functions, social order, resources, and etc., which have brought inconvenience to people’s daily work and travel. It is one of the practical problems that restrict the sustainable development and the developing level of the cities in China [3]. Some studies have highlighted the effect of spatial layout and drainage network structure (e.g., diffuse width, mantle depth) in impermeable areas on urban rainwater exclusion, particularly peak flow [4–6]. The urban rainwater pipe network is one of the important infrastructures in the city. The reasonable planning of the rainwater pipe network is the key link to ensure that urban rainwater could be fully and smoothly drained.

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However, in reality, because of the design and planning concept, and the construction of municipal facilities system failing to catch up with the speed of urbanization, there are numerous defects of most urban drainage system planning. Some extreme weather such as rainstorms has caused severe waterlogging in many cities and posed a serious threat to the lives and property of the people. The most significant characteristic of rainwater drainage system is hidden, so the initial planning and design are particularly important. In order to plan urban rainwater drainage systems more reasonably, rainfall runoff models have been gradually introduced into urban rainwater network planning. The common rainfall runoff models include CMSS [7], SLAMM [8], HSPF [9], SWMM [10], and others. The SWMM, a storm runoff management model, was introduced by the US Environmental Protection Agency to solve the increasingly serious problem of urban drainage. This model can dynamically simulate rainstorm runoff generated by a single rainstorm or continuous rainfall, and to solve the problem of water quantity and quality related to urban drainage system [11]. In recent years, the application of SWMM has been extended to recharge groundwater [12], assess water pollution [13] and so on. Meanwhile, the model has also been gradually applied in rainwater pipe network planning in some cities in China [14–17], and a series of studies are carried out, such as parameter calibration [18], pattern-oriented approximation and optimization objective [19] and etc. Due to the characteristics of urban surface and the complexity of rainwater pipe network, the simulation and construction of urban rainwater pipe network model based on SWMM have become a tedious and complicated task. And the hydrological models have advantages to assess the impacts of spatial patterns on urban rainfall runoff processed at multiple spatial scales [20]. The spatial analysis, network analysis and other functions of GIS can effectively support the construction and optimization of the urban drainage pipe network.

In this study, a typical town with perennial waterlogging was chosen as the research area to obtain its original drainage system and optimize it. The SWMM model was utilized to acquire reasonable values of hydrological parameters for the dynamic simulation of hydrological information of the surface in the planning area. In addition, this paper introduced the hydrological analysis function of GIS based on SWMM model, which made the extraction of the inlet and outlet in a rainwater pipe network more effectively, and realized the rapid layout of rainwater pipe network, the extraction of hydrological parameters and the simulation of hydrological model. Simultaneously, the layout of the existing road network was considered in this paper, the rainwater pipe network can be preliminaries planned, which could reduce maintenance if it was arranged along the road network. Consequently, the data from various sources can be obtained from an integrated platform, which greatly improved the conversion and transmission rate of data, saved the unnecessary communication costs in different software systems, and realized the comprehensive optimization and intelligent layout of rainwater pipe network.

2. Research Area and Analysis of Surface Features

2.1 Overview of the Study Area

This paper took the rainwater engineering design of a new town in Huichang County, Jiangxi Province as the research example. The township located in the northwest of Huichang County, and the provincial highway “Huishang Line” runs through the whole territory, furthermore, Xiamen-Chengdu Expressway exits directly into the town. It is 15 kilometers from the town to Xijiang Railway Station. Gongshui River and Anyuan Rivers pass through the town and the traffic is very convenient. This town is situated in the subtropical monsoon region, with four distinct seasons, sufficient rainfall and abundant sunshine. The average annual rainfall of the study area is 1624 mm, and the average annual surface runoff volume is 218.80 billion cubic meters. It is rainy in spring and summer, but rainless in autumn and winter. Especially in April to June, rainfall is concentrated, with an average of 752.9 mm, accounting for 48.4% of the total annual rainfall, which frequently causes floods and waterlogging. While the average annual rainfall from July to September is only 388.1 mm, accounting for only 24% of the total annual total. The terrain of the study area is high in the west and low in the east, with the northwest inclined to the southeast and denudation to form hilly landforms. The elevation range of altitude is 130–170 meters, the relative elevation is 40 meters, and the slope is between
15–20 degrees. The study area can be classified as a low hill type by elevation and slope. The total land area is approximately 261.34 hectares, which is an irregular and narrow strip-shaped basin.

The artificial drainage system in the study area is imperfect. There are just a few drainage facilities and the drainage facilities are not systematic. Therefore, the original drainage facilities cannot be included in the new planning, and it is necessary to establish a systematic drainage network according to the new land use layout. At present, the commonly used drainage system includes diversion system and interception confluence system. In order to improve the living environment, increase drainage efficiency, and reduce possible urban waterlogging, this paper adopts the diversion system.

### 2.2 Analysis of Surface Features

Most of the land use for the current status of the town are classified as Class I and Class II land, while the surrounding land is classified as Class III land. The appropriate development and construction shall be carried out through the measures of filling and excavation, moreover, the specific classification criteria of land use type refer to the national regulations. As shown in Figure 1, major changes have taken place the types of land cover before and after development have undergone major changes, and the original farmland, grassland, and woodland have been developed as construction land, especially in the southeast and northeast of the study area, it was forest and farmland before the development, while it is residential area now. This transformation caused the urban impervious area has increases significantly, at the same time the surface infiltration and interception capacity of rainwater also decreased. Meanwhile, surface elevation also changed with the planning of roads and the demand for drainage. From this point of view, before and after the development of the study area, the changes in the terrain, landform and the cover of the surface had a significant impact on the formation of rainfall runoff, and the area of water accumulation were changed as well.

### 3. Seamless integration of SWMM Model and GIS

#### 3.1 SWMM Model Source Code Analysis and Compilation

The SWMM model used in this paper is version 5.0 and consists of 7 header files and 43 C code files, which are divided into four calculation modules and one service module simultaneously. Among them, four calculation modules are Runoff, Transport, Extranet, and Storage/Treatment [14], which can respectively realize the simulation of surface runoff, pipe network transmission and sewage treatment units in urban drainage systems. The main function of the service module is to perform some post-calculation processing, such as statistics, drawing and so on. SWMM model source code can be compiled as: (1) Windows dynamic link library (DLL); (2) Standalone console application (SCA) under Windows and Linux; (3) A shared object library (SOL). These

![Figure 1. The comparison of the new town coverage between before and after the planning.]
three compilation strategies depend on the declaration of #define DLL, #define SCA, and #define SOL that begins in the file SWMM5.c. In order to realize the seamless coupling between SWMM and ArcGIS Engine components, this article compiled it into a Windows DLL. There are three approaches to generate a DLL: (1) Through the SWMM5.EXE provided by the SWMM model, and the SWMM5.dll that is a dynamic link library file will be existed in the installation folder directory. (2) To load the source code into VS2010 and generate the DLL through the source code compiler. (3) To compile the source code by using the command line in the CMD console. This paper utilizes the second method to compile and generate the SWMM5.dll dynamic library.

3.2 Secondary Packaging of SWMM5.dll

In order to realize the seamless integration of SWMM5.dll with GIS components, and SWMM5.dll is re-encapsulated by C# language to generate a .Net managed development package named SWMM5Mgr.dll, which has high development efficiency and is widely used by GIS engineering application development. The DllImport attribute method provided by C# can realize the interoperability of the SWMM model. This attributed method is exposed by making an unmanaged dynamic link library as a static entry point, with four optional attributes, such as EntryPoint, CharSet, SetLastError, and CallingConvention. The EntryPoint indicates the entry point name of the exported DLL function, CharSet is used to set the incoming character format, SetLastError can indicate the wrong way to handle it, and CallingConvention is used to indicate to the CLR that the function call convention is used for the parameters in the stack. The sample code for calling SWMM5.dll in C# is as follows:

```csharp
[DllImport("SWMM5.dll", CharSet=CharSet.Ansi, CallingConvention=CallingConvention.Cdecl)]; // Introduced DLL private static extern int swmm_run(string f1, string f2, string f3); // Declare method public int swmm_run (string [] args) // Redefine the calling method { int r; r = swmm_run(args[0], args[1], args[2]); return r;}
```

3.3 Seamlessly Coupling SWMM5Mgr.dll in GIS Components

This paper seamlessly coupled the SWMM model with ArcGIS Engine components under the .Net development environment. The coupling enabled them to have a unified interface for data manipulation and an interactive interface, which can realize data barrier-free sharing and exchange with each other. The coupling mechanism and working mode are shown in Figure 2. The coupling between the SWMM model with ArcGIS Engine components can bring into full play to their respective advantages. The GIS component is in charge of extracting and calculating the data, such as catchment areas, gutter outlets, pipe network layouts and rainfall data, and converting the calculation results into the input data format file as *.inp of the SWMM model. The SWMM model is used to perform the simulation and return the results to the GIS component for the next step to calculate or adjust the parameters of rainwater pipe network parameters. The core modules of the coupling model include the automatic construction of the pipe network, the runoff simulation, the rainwater pipe network calculation and the storm flooding analysis.

4. Automatic Extraction of Hydrological Parameters Based on GIS

4.1 Building of DEM

The planning of the urban road network and the land use have changed the natural surface of the earth’s surface, and the original terrain can no longer be used for watershed hydrological analysis of the rainwater pipe network. Consequently, a new DEM shall be constructed on the basis of the basic planning data. Meanwhile, the characteristics of the layout of the rainwater pipe network along the road must be taken into consideration. When constructing DEM, the planning area was first segmented by a road network and each sub-block constructed a DEM independently. Secondly, the planned elevation value of the road was used as the data source, and the surrounding land was used as the obstacle. And then spatial interpolation of the road is performed by Kernel Interpolation with Barriers to generate road DEM, as shown in Figure 3. Since the road rainwater inlets is usually lower than the ground level of the adjacent blocks,
the rainwater will not flow out of the road again after entering the road and before overflowing. In the case of ignoring the drainage of the road slope, the road grid was modified to reduce the grid on both sides of the road center-line by a certain value and then gradually buffered to the sides of the road according to the width of the road, which could create a continuous inclined plane from the center-line to the red line of the road. So that the accumulated water on the road can be efficiently collected. The DEM of each sub-block was generated by the inverse distance weight (IDW) interpolation method under the constraints of the elevation that was designed by the road network and each land plot, as shown in Figure 4.

4.2 Division of Catchment Districts and Automatic Extraction of Catchment Points

In addition to topographic factors, the distribution of rainwater pipe networks and the layout of cities are the major factors affecting the division of urban rainwater catchment district. While the main effect factors for the new urban areas are the urban layout, namely the road network and land use planning. The DEM based on the
layout of the new city is a considerable guarantee for effectively dividing the catchment districts. When separating the catchment district, the broken area can be appropriately merged. As shown in Figure 5, the sub-basin of the research region was divided into 22 catchment districts. At the same time, the catchment district was vectorized so that it can be superimposed with the land planning and utilization elements. In this paper, water outlets of the catchment district were generalized into the water inlets of the rainwater pipe network. The design elevation of the road was assigned to the newly added inlets, and the rainwater inspection wells were established up at the intersection of the road network, as demonstrated in Figure 5. Moreover, the rainwater in the catchment district may flow directly into the inlets and into the rainwater pipe network, and perhaps it may flow from one catchment district to downstream one. The distance between urban secondary trunk roads is generally 300~400 m, and the plot area is not extremely large. Therefore, this situation is less likely to appear in areas. When the exchange of water flow occurred between catchment districts, these catchment districts can be combined. In addition to water outlets of the catchment district, the inlets of the rainwater pipe network also contain rainwater inspection wells installed at all intersections of the road network. All the intersection points in the network should be configured as rain water inspection wells. There may be inspection wells with zero rainwater flow, which could be deleted when calculating the design flow of the pipe section.

4.3 Automatic Collection of Watershed Parameters

The value range of hydrological parameters such as diffuse width, Manning coefficient, mantle depth, and infiltration parameters in the confluence area could be determined based on literature data, and then the characteristic values of the research region can be calculated by the pass rate determination. The remaining parameters could be obtained directly by using GIS spatial analysis methods through the file. When simulating the rain flood in the planning area, it is necessary to acquire some parameters such as the proportion of impervious area, the roughness of the permeable surface, the ratio of the impervious surface area, the surface Manning coefficient, the depth of the sluice, the infiltration rate, the characteristic width, and average slope etc. in the catchment area. At the same time, the land in the catchment area was reclassified into permeable area and impervious area. The permeable land includes communal green areas, protective green areas, and residential green areas. The impervious land includes construction land and road plaza land. The parameters are gained by various means, such as: (1) Average slope: based on the DEM constructed in 4.1, the slope analysis was performed and the slope analysis value was superimposed with the catchment area, and the average slope in each catchment area was counted. (2) The longest diffuse flow path: on the basis of the DEM constructed in 4.1, the longest diffuse flow path in the catchment area was obtained by hydrological analysis tool; (3) Feature width: the feature width of the catchment area was a significant parameter in the model, which was sensitive to the simulation of water quantity. Therefore, the accuracy of the feature width would affect the prediction results of the model [21]. However, the feature width of each sub-water area is usually difficult to identify. According to the SWMM model user manual, the ratio of catchment area to the longest path of surface diffuse flow was recommended in this paper; (4) Area ratio of pervious and impervious areas: the superposition analysis component of GIS was used to calculate the superposition of water collecting area and land use data to obtain the area and proportion of water permeable area and impervious area respectively; (5) Surface roughness:

![Figure 5. Computing the watersheds and sinks.](image-url)
on the basis of the calculation results for slope, the surface roughness was acquired by the reciprocal of the cosine of the slope. This parameter was superimposed with the permeable and impervious areas of the catchment area to obtain the surface roughness and impervious area roughness of the catchment district; (6) The depths of storage in permeable and impervious areas were evaluated according to the characteristics of the surface and norms. By means of the defined parameter acquisition, the automatic extraction consequences of catchment parameters in the experimental area of the planning area are illustrated in Table 1.

5. Automatic Layout and Optimization of Drainage System

5.1 Weight Model of Urban Storm Pipe Network

In addition to meeting the drainage requirements of the planning area, the project of urban rainwater pipe network should also take cost into consideration. Currently, the calculation of the cost of the drainage pipe network usually adopts an enumeration algorithm to combine the design parameters and assign different weights. Through this algorithm, a combination with the lowest cost of the pipe network could be obtained [11,22,23], so that the design of the drainage pipe network would be optimal. The cost of the pipe network was shown in formula (1). Pipeline costs are linked to factors such as pipe diameter, slope, depth, and flow rate [11,22–24].

\[
M = \sum_{i=1}^{n} f \left( w_i S_i, w_2 L_i, w_3 H_i, w_4 Q_i \right) \tag{1}
\]

In formula (1), \(M\) is the total cost of all pipe sections; \(S_i\) is the road surface slope of section \(i\); \(L_i\) is the length of the road surface of section \(i\); \(H_i\) is design elevation of the road surface at starting point of section \(i\); \(Q_i\) is the inflow of the starting point of the pipe section; \(w_1, w_2, w_3,\) and \(w_4\) are the corresponding weight of each factor;

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<th>Characteristics of the width</th>
<th>The average slope (%)</th>
<th>Impervious area ratio (%)</th>
<th>Impervious Manny coefficient</th>
<th>Pervious Manny coefficient</th>
<th>The depths of storage in impervious area (mm)</th>
<th>The depths of storage in pervious area (mm)</th>
<th>No-depression storage area ratio (%)</th>
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is the number of designed segments. In the above parameters, $S_i, L_i, Q_i$ and $n$ are positively correlated with $M$; $H_i$ determines the buried depth of the pipe network, which is also positively correlated with $M$.

Considering the impact parameters of rainwater pipe network design, in this paper, the weighting factors of rainwater flowing into the pipe network are divided into two categories: edge weight and node weight. The edge weighting factors include the slope, length, and grade of the road, the node weighting factor is the rainfall flows into the water inlet of the catchment area. The influence of each factor on the direction of water flow in the pipe network depends on the environment, in which the rainwater pipe network is designed. In different environments, the weights of impact factors are also different, which can be weighted by evaluation methods such as expert evaluation method, economic analysis method, operations research and other mathematical methods, mixed methods, and AHP decision analysis methods. In fact, due to the fact that the actual operating environment of the rainwater pipe network varied widely, it is not easy to determine the exact weight of the factor.

Although it is difficult to determine the exact weight values of these impact factors, the primary and secondary relationships and approximate value ranges between them can still be explored. It may be assumed that the starting point of the two ends of the road $R$ is $A$ and the ending point is $B$. The flow direction of the rainwater in the pipe network is determined according to the principle that the rainwater flows from the higher end to the lower end of the ground in the pipe network. Assuming that the elevation of the A-end is greater than the B-end, then the weight $w_3$ of A to B would be set as a positive number, and vice versa. Secondly, it is necessary to drain rainwater into the river nearby as quickly as possible. The water flows from inlet to outlet of a rainwater pipe network according to gravity, and there are $n$ routes in its outflow path. Then, the length and the buried depth of the pipeline can be calculated by the slope and the elevation difference of the road surface. Finally, the bearing capacity of the pipe segment is related to the amount of rain flowing into the water inlet. When rainwater flows to the next node, the negative weight could be directly considered impassable. And then the probability of the next node with other positive values was compared. To be implemented in programming, slope is defined in this paper to describe the factor. The larger the slope is, the greater the corresponding weight $w_1$ will be. Similarly, the length of pipe segment and the inflow rate of the starting point node are larger, and the corresponding weights $w_2, w_4$ are also larger.

5.2 Rainwater Pipe Network Deployment Based on Weighted Directed Geometric Networks

Since the study area is a small town, and the width of the planned road is not greater than 40 meters. Thus, depending upon design specifications, a single drainage pipe is laid along one side of the road, as well as the collected rainwater from the other side is connected through the side pipe. The paper used the component of INetworkLoader in ArcGIS to automatically create a geometric network. The methods in this interface such as LoadNetwork (Generate a geometric network), NetworkType (Define geometric network types), AddFeatureClass (Add features to a geometric network), and AddWeight (Add weights) were applied to create a geometric network. “From-to” weight, a weight of geometric network edge, was abbreviate as FT and “to-from” weight was abbreviate as TF. In order to facilitate the construction of geometric networks, water outlets of the catchment district was projected onto the centerline of the road and assigned an initial weight value to each pipe segment and pipe point, as shown in Figure 6(a). Then, the initial network was optimized by using the geometric network analysis module provided by InetworkLoader which being the geometric network component. At the same time, Junctions, Outfall, and DrainageNetwork were taken as input parameters to calculate the optimal route from each geometric network to the outlets of each gully. All of optimal routes constituted the optimal layout of rainwater pipe network, and the number of pipe sections from the rainwater inlets to the outlets was calculated and a drainage line for the same node was established, as shown in Figure 6(b). Compared Figure 6(a) with Figure 6(b), the weight of the pipe network made the rainwater drainage network greatly optimized and the layout more reasonable.

5.3 Simulation of Rainfall Runoff Process and Optimization of Pipe Network Layout

This paper outputs the hydrological parameters and
rainfall data gathered in the catchment district above were output as *.inp files and used as the input parameters of the SWMM model. It applied the model of the runoff module to invoke the parameters in the input file to simulate the rainfall and runoff processes, in addition to calculating the rainwater network flow rate which pipe section design. Before executing the simulation, the model parameter options must be set, which including: loading the road network, DEM, and other layer data, selecting the infiltration model of the pervious zone, inputting the surface evaporation constant, setting the model’s calculation step and flow unit, and inputting the region’s rainfall time series. After the parameters were adjusted, the simulation was performed and a watershed simulation file was generated. The file contains rainfall data, catchment data and outfall data. And this paper corresponded to the outlets of each catchment district, so as to prepare data for further calculation of the peak runoff in the catchment district.

The simulation file of the catchment district was used to calculate the flow rate, and the peak runoff in the catchment district was output to the inflow of the outlets of the corresponding catchment district, that was, the inflow to the inlets of the rainwater pipe network. Along the horizontal layout of the rainwater pipe network, the lateral flow of the pipe section was computed according to the descending order of the drainage line of equal nodes. The sum of the inflow and side flow is the designed flow of the pipe section. It is an important parameter for calculating the pipe diameter, slope, slope drop, flow velocity, depth of burial, and designed elevation of the bottom of the rainwater pipe network. This paper traversed all the gutters of the pipe network, and excluded the node whose design flow is 0, simultaneously, the corresponding upstream pipe segment of the pipe network was deleted. At the same time, the design flow of the pipe section and the layout of the rainwater pipe network were updated in the database. As shown in Figure 7(b), the labels in the figure are the design flow and the catchment district number of the pipe segment respectively. The pipe section design flow rate was calculated according to the rainstorm intensity with a return period of 100 years. Compared with Figure 6(b), the optimized rainwater pipe network has a certain change in layout. The flow of rainwater outlets at the upper left corner of the road is 0, so the outlets and the connected pipe segment were deleted.

5.4 Flood Analysis of Pipe Network

The purpose of the flood analysis of the pipe network is to adjust the overflow nodes and the overloaded pipe sections. The transport module of the SWMM is responsible for studying the transportation simulation of the regional rainwater pipe network transmission. And according to the simulation results, pipe node parameters and vertical parameters of the pipe segment were re-adjusted for the overflow node and the overloaded pipe segment. First, as shown in Figure 8(a), the parameters
of the catchment district, the layout of the rainwater pipe network, the parameters of the rainwater pipe network, and the rainfall data were output as *.inp files as the input parameters of the SWMM model. Then, the overflow node and segment flow process line function was called to check the overflow node and the overloaded segment. As shown in Figure 8(b), the parameters of the catchment area and the rainwater pipe network were output as sub-basins, pipelines, intersections, etc. of the SWMM model by using the rainwater pipe network simulation file. The flow calculation process model of SWMM was called to simulate the rainwater transmission in the rainwater pipe network, and according to the returned data, check whether there is an overflow node and an overload pipe segment. As shown in Figure 9(a), the pipe segments as C21, C22, and C23 were overloaded. The system would record the pipe sections that need to adjust the parameters, and then it would manually adjust the pipe diameter parameters of the overloaded pipe section and recalculate the pipe segment parameters of the drainage system according to the adjusted parameters: pipe diameter, slope and flow rate. The vertical parameters of the adjusted rainwater pipe network were recalculated, the rainwater pipe network simulation file was regenerated, and the rainwater flooding analysis was performed again. If the overflow nodes or overloaded pipe sections still existed, the above optimization process was repeated until the overflow and overload were within a tolerable range. In the process of continuous adjustment, with the change of the parameters of the pipe segment, the construction cost of the project is also changing, so it is necessary to combine the manual judgment when selecting...
the optimal program. The final layout of the rainwater pipe network design in the study area is shown in Figure 11. The labels in the figure are the design elevation of the ground and the design elevation of the pipe bottom, the design slope of the pipe section and the design pipe diameter.

5.5 Comparison with Traditional Rainwater Pipe Network Design

In order to reflect the more reasonable, more scientific and efficient deployment of the rainwater pipe network layout adopted in this paper, the research results of this paper were compared with the existing traditional planning schemes in the study area. Traditional programs are mainly based on certain norms by planning experience of planners and related knowledge. The planning is relatively random and cannot effectively divide the drainage area of the planning area, which is the premise for the effective and reasonable distribution of rainwater pipe network. Figure 11 is a part of the rainwater pipe network plan designed by the customary planning scheme of the study area. The results of this method are quite different, which are shown in the following aspects:

1. Design of water outlets: Figure 10 is a single drainage area based on the grid DEM and applied to the GIS digital watershed analysis component and the outlets of the drainage area were used as the outlets of the rainwater pipe network. In Figure 11 based on topographic fluctuation and previous experience, the engineer did not set up a drainage outlet in the study area, but drained rainwater from the study area to another area. However, it would enhance the load on the water outlets of another drainage area, which may cause waterlogging.

2. Arrangement of water inlets: The water inlets in Figure 10 were divided into multiple catchment areas in the drainage area by utilizing the GIS digital watershed analysis component. Furthermore, each water catchment outlets were served as the inlets for each pipe section, and an inspection well was set at every intersection of the roads. However, in Figure 11, the rainwater pipe network inlets were only roughly set at or near road intersections, without taking topographic factors into consideration. Therefore, rainwater in corresponding ground area cannot be fully collected by the arranged inlet.

3. The layout of the pipe network: the rainwater pipe network in Figure 10 formed a complete directed network covering the entire drainage area. At the same time, various weighting factors of each pipe segment were fully considered in the process of network deployment. Therefore, the designed rainwater pipe network layout was more reasonable and effective. As shown in Figure 11, the conventional scheme mainly lays the main water pipe section along the main road, and then lays out the water pipe section according to the secondary road topography, and the
rainwater pipe network in this figure did not form a complete network. At the same time, the total length of the designed pipe network was larger than the total length of Figure 10, which not achieved effective drainage, but also increased the project cost.

(4) Parameter design of the pipe network: as can be seen from Figure 11 the diameter of the rainwater pipe is basically designed to be 300 mm and 400 mm. In this way, the design mainly relies on the engineer’s design experience and traditional budget estimation strategy. The design range of rainwater branch pipe in Figure 10 is 200 mm~800 mm, and the main trunk of rainwater is 1000 mm. Since the pipe network in Figure 10 was automatically set by the system according to the terrain and calculation results, and through the overflow node and the overload pipe section inspection, the designed pipe section parameters were superior to the conventional ones. At the same time, the pipe diameter, slope, design elevation and other parameters of the pipe network in Figure 11 were recorded into the system developed in this paper. The simulation results show that there were two pipe sections overloaded, and the fullness of one pipe section in the whole rainfall process was less than 0.1.

6. Conclusion

In order to ensure that the rainwater pipe network in the newly built city can meet the expanding needs of modern cities, the design of the urban rainwater pipe network usually needs to consider the surface runoff in the planned area within 15~20 years. Therefore, the current urban rainwater pipe network planning method has been challenged. In order to solve the backward situation of the traditional urban rainwater network planning, the paper puts forward the integration of urban hydrological model SWMM and GIS component integration to construct a powerful rainwater network. From the research results, the following points are recognized:

(1) Planning the regional planning road, vertical design data, planning land type and other basic planning data are the important basis for accurately constructing the new urban areas DEM and extracting hydrological parameters, thus directly affecting the designed results of urban rainwater network.

(2) The GIS hydrological analysis function is scientific and reasonable enough to realize the urban rainwater network layout according to the drainage area, and can accurately and efficiently extract all the water inlets and outlets of the rainwater pipe network. At the same time, the function of network analysis in GIS could realize the rapid layout of urban rainwater networks, thereby greatly improving the work efficiency.

(3) The urban hydrological model SWMM can be used to dynamically simulate the hydrological information of the surface of the planning area, so as to pro-
vide reasonable hydrological parameter values for the construction of the rainwater network.

(4) The value of hydrological parameter weight has an important influence on the planning result. It is an important part of urban rainwater network planning to reasonably assign the weight of hydrological parameters.

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**References**


[16] Chen, L. Q. (2010) A study of the suitability of SWMM to plan and design the rainwater pipe network


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