International Journal of Hybrid Information Technology
Vol. 9, No.11 (2016), pp. 25-34
http://dx.doi.org/10.14257/ijhit.2016.9.11.03

Applications of GIS in Information Management for Urban Rainfall-Runoff Simulation

Ji Shen and Qiuwen Zhang

College of Hydropower and Information Engineering, Huazhong University of Science and Technology, Hubei. China, 430074
shenbx1987@163.com

Abstract

Researches for urban rainfall-runoff simulation are inseparable from the hydrological information. However, this information is always composed of large amount of multi-source and heterogeneous data, which will bring significant difficulties to the information organization and management systems. In this paper, Geographical Information System (GIS), a specialized information system for the spatial information is introduced into the studies of urban rainfall-runoff simulation (URRS), in which a series of applications are presented. In these applications, hydrological information in urban region is collected, stored and processed by the spatial data storage, analysis and visualization abilities of GIS. The applications show that the integration of GIS and hydrological information is feasible in URRS and has achieved remarkable results, which can provide a strong data support to the simulation and control of urban storm water disaster.

Keywords: *Urban Rainfall-Runoff Modeling (URRS); Data Organization and Management; GIS, Hydrological Information; Spatial Analysis; Visualization*

1. Introduction

Nowadays, storm water disasters have brought great threatens and caused huge losses to the people's lives and properties [1]. In recent years, with the acceleration of urbanization, city has become one of the worst-hit areas of storm water disaster[2]. As a result, significant attentions have been paid to the prevention and control studies of urban storm water, which include urban storm risks evaluation[3,4], hydrological parameters estimation[5], runoff processes simulation[6], losses assessment[7,8], et al. All these researches above can hardly carry out without the hydrological information, especially for the URRS, a hot research topic in the study of urban storm water disaster. URRS is actual a thematic distributed hydrological modeling method for the urban storm water, and it is able to provide a mathematic description for the physical process of urban rainfall event.

Hydrological information is the data basis of the URRS, which is closely related to the input and output of the model. As hydrological information plays quite important roles in the URRS, it is necessary to develop a reliable information system for data organization and management, which can finish the following works:

1. Hydrological information collecting and storing. Hydrological information first needs to be collected from the studied urban watershed and stored into the data files, which can be imported into the model before the simulation starts.

2. Hydrological information processing. After the collection, they need to be preprocessed, merged and modified before they meet the model requirements.

3. Hydrological result information displaying. After simulation, the results of URRS are also hydrological information that with various types and visibility. All this results need to be displayed in vivid and intuitive ways.

In previous studies, these works are often completed by Management Information System (MIS), Relational Database Management System (RDBMS) and Computer

ISSN: 1738-9968 IJHIT

Aided Drafting (CAD) software, but the actual performances are always disappointing. The main reason is that hydrological information is very special and has its own characteristics as follows [9]:

1. Hydrological information is massive and diverse. There are large amount of hydrological information with different data types that need to be imported into and output from the URRS.

2. Hydrological information is heterogeneous and from multi-sources. Each type of information may have its own source and data structures.

3. Hydrological information is spatial and non-uniformity. A considerable percentage of the hydrological information is relative to the spatial locations, and therefore will be greatly impacted by many space parameters.

According to the characteristics of hydrological information, how to provide a reliable and effective organization and management for the complex hydrological information is the core problem in this study, and the traditional methods always cannot achieve. GIS is a strong information management technology that is able to process various kinds of information with spatial characteristics and provide powerful spatial query, analysis, statistics and graphic-attributes integration management functions. In this paper, we try to apply GIS in URRS to solve the above problem. On the platform of GIS, the hydrological information is integrated with the URRS, which can further improve the simulation results of URRS.

2. GIS-based Hydrological Information Collecting and Storing

2.1. Information Collecting for URRS

URRS requires a great deal of hydrological information, which includes rainfall records, topography data, drainages distribution, buildings and other model parameters (slope, width, Manning's roughness, depression storage, infiltration rate, et al). As URRS is actually a distributed hydrological model, in order to reflect the spatial variability in topography and hydrological information, the entire watershed of study area need to be divided into several sub-watersheds. Each sub-watershed has its own runoff processes that will be calculated independently in the URRS. Thereby, all the hydrological parameters should be collected and stored in the units of sub-watershed according to their spatial locations. However, the sub-watersheds are spatial data, while the hydrological parameters are attribute data. The spatial data and attribute data are usually organized by different methods which are independent with each other in traditional management model of URRS. Concretely, the DBMS is applied to the management of attribute data while the spatial data are stored in the format of CAD. No significant association is established between two data management methods, which will bring obvious difficulties in the integration query for two types of hydrological information, as shown in Figure 1 (a).

2.2. Hydrological Information Storage Method Based on GIS

In this paper, in order to solve the problems above, the sub-watersheds and the hydrological parameters are stored in the format of shape file based on GIS, as shown in Figure 1 (b).

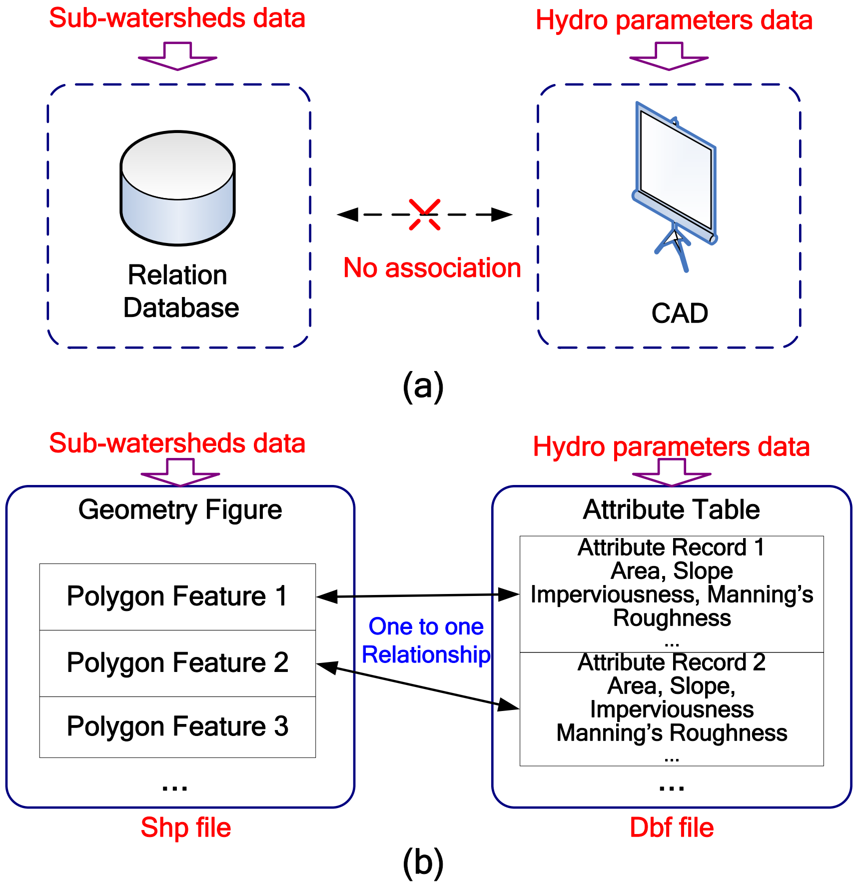

Figure 1. Data Storing Structure of the Sub-watersheds and Hydrological Parameters. (a) Traditional Method. (b) GIS-based Method

Shape file is a vector data format in GIS, which can describe not only the geometric position, but also the attribute characteristic for the spatial objects. Shape file is actually a file set that consist of multiple different types of data files. Three indispensable files of shape file are:

1. Shp file: The main file that stores the geometry figure for the spatial features.
2. Shx file: The index file that stores the index of the spatial features in the shp file.
3. Dbf file: The dbase file that stores the attribute information of spatial features.

After the division of sub-watersheds is finished, each sub-watershed is converted into an irregular polygon feature, which can be stored in shp file, and form the spatial polygon layer of sub-watersheds. Then according to the spatial distribution of the sub-watershed, all the hydrological parameters can be collected and stored in the data table of dbf file. There is a one-to-one relationship between each sub-watershed polygon in shp file and record in the data table of dbf file, which can be organized and managed together according to the feature ID (FID), as shown in Figure 1.

2.3. Graphic-Attribute Integration Storage for Hydrological Information

The data structure of shape file achieves the aim of graphic-attribute integration storage for the hydrological information which does not provided by the traditional data management model in URRS. If a sub-watershed is selected in the map, its hydrological parameters will be picked out from the attribute table, and displayed beside the spatial graphics of the selected sub-watershed, as shown in Figure 2.

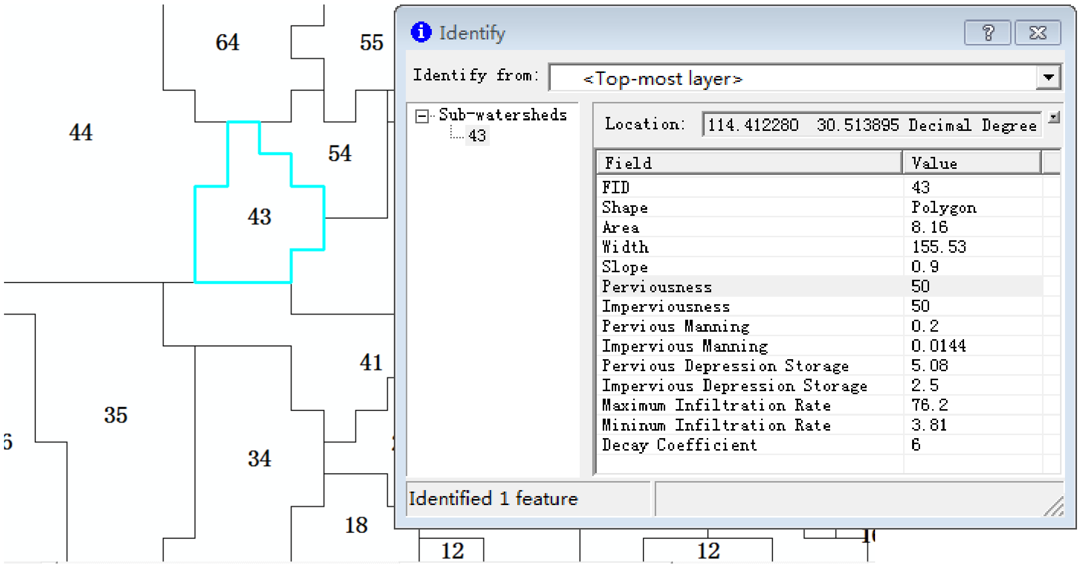

Figure 2. Interactive Query between Graphic and Attribute in the Shape File of Sub-watersheds

Similarly, the hydrological information of drainages and buildings can be also collected and stored in the form of shape file from this kind of interactive management. The applications of GIS in the collecting and storing process of hydrological information can provide an advanced data organization method[10], which can make the data input of the URRS better reflect the actual hydrological features of the urban region.

3. Using GIS to Process and Analyze the Hydrological Data

URRS is an integrated distributed hydrological modeling method that is able to simulate entire hydrological processes of rainfall, surface and drainage runoff. As a result, different types of hydrological information from different sources need to be considered at the same time in URRS. In order to integrate the closely related hydrological information together, the spatial analysis functionality of GIS is adopted to process the hydrological data in URRS.

3.1. Data Processing in Division of Sub-watersheds

In URRS, one of the most important steps that involve data processing is the division of sub-watersheds. Sub-watersheds are collecting, storing and simulating units of URRS, the spatial distribution of sub-watersheds embodies the spatial no uniformity of the hydrological information in the urban region. As a result, the division results of sub-watersheds will directly affect the performance of URRS. The traditional division methods for the sub-watersheds are always based on the DEM data and flow direction calculation results from D8 algorithm [11], which can describe the natural terrain and surface runoff and confluence conditions of urban region. The traditional DEM data can only reflect the spatial distribution of natural river system without considering the artificial runoff path that is composed by road and drainage in urban area. However, there may be no significant water system in the study urban watershed, and the roads and drainages flow systems are actually the runoff approach of the storm water. Thereby, the runoff processes in urban region are not just influenced by the topography condition, but also closely related to the spatial distribution of roads and drainages systems in urban region. In order to ensure that hydrological features of the urban region can be well reflected in the spatial distribution of sub-watersheds, the DEM data and distribution of roads and drainages systems are combined together by GIS.

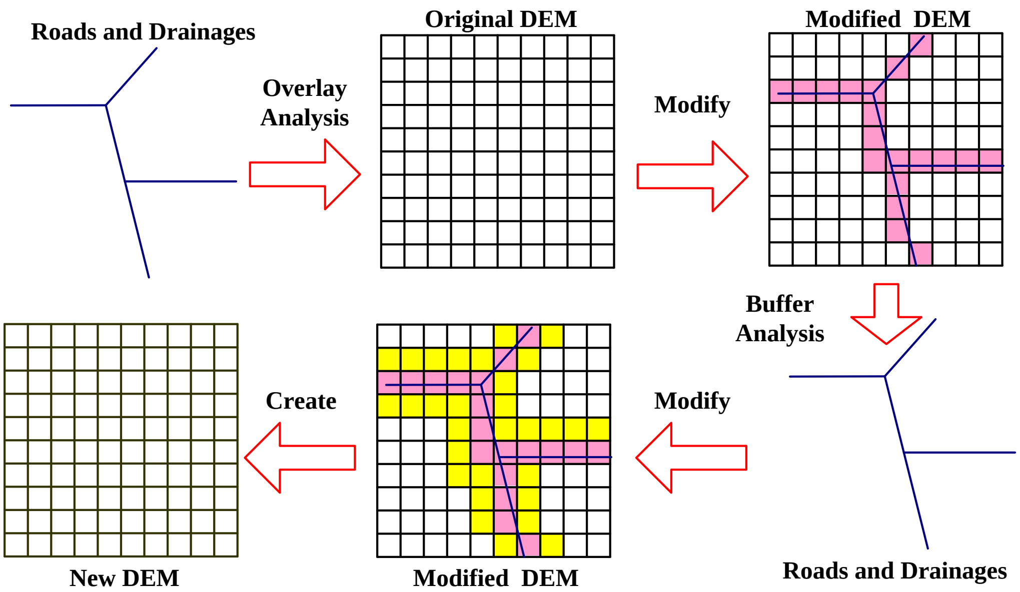

Figure 3. Information Processing of the DEM Data by Using the Spatial Analysis in GIS

In GIS, the DEM data, roads and drainages data can be stored and processed in the format of raster layer and polyline feature layer, respectively. To combine them together, according to the spatial distribution of the roads and drainages, the DEM data are modified based on the applications of overlay and buffer analysis function in the GIS [12], as shown in the Figure 3 and following steps.

1. Overlay the roads and drainages layer to the DEM layer, and get the collection of DEM pixels where the roads and drainages polylines are located.

2. Reduce the elevation values of the DEM pixels in the collection according to the levels of the roads and drainages. For the trunk roads and drainages, the elevations are decreased in greater degree. For the branch roads and drainages, the decreasing value is smaller.

3. Using the buffer analysis to calculate the buffer area of the roads and drainages for a certain distance, and get the collection of DEM pixels in the buffer area.

4. Reduce the elevation values of the DEM pixels in the collection according to the distance from each pixel to the road or drainage polyline, the closer from the pixel to the polyline, the larger the decrease value is.

5. Create a new raster layer to store the modified DEM data that will be adopted in the division of sub-watersheds.

Based on the data processing of GIS, the elevation values of the DEM pixels which intersect with and near the roads and drainages are smaller in modified DEM data than the values of same pixels in traditional DEM data. As the water always collects in the hollows under the action of gravity, the runoff of the rainfall will gather at the roads and drainages, and then flow along them according to the terrain topography in the modified DEM, which is accordance with the actual rainfall and runoff processes in the urban region. In this way, the topography features in the modified DEM data can describe hydrological characteristics of urban watershed, which can make the division results of sub-watersheds in URRS more reasonable.

3.2. Data Processing in Parameters Collection of Sub-watersheds

After the division of sub-watersheds, the model parameters can be collected and estimated for each sub-watershed. However, these parameters usually need to be extracted from different pieces of basic data of the urban watersheds, which are often stored in the different data format or independent structure, thus bring significant difficulties to the collection of model parameters. In this paper, the spatial analysis methods of GIS are used in the parameters collection work of URRS. Considering the hydrological parameters of each sub-watershed are usually closely relative with DEM or RS image, take the Imperviousness, one model parameters of URRS, for instance, it can be calculated and collected by overlaying the sub-watersheds layer with the layers of RS image [13].

In URRS, the surface of urban region is divided into two types according to the permeability values: the previous and impervious surface. As the runoff processes of these two types of surface are simulated by different methods, and some other model parameters are evaluated based on the area ratio of different pervious surface types, the collection and evaluation result of imperviousness in each sub-watershed is particularly critical in the simulation of URRS.

The imperviousness of each sub-watershed is closely related to the land cover type of urban surface [14]. There are different pervious surface coverage values in different land cover types. For example, the grasses cover usually has high permeability, and the pervious surface coverage is over 70%; the pervious surface coverage asphalt or concrete paved surface is quite low, which is about 0-20%. In order to simplify the collection work of imperviousness for each sub-watershed, the land cover types with pervious surface coverage more than 50% are classified into the previous surface type, and the land cover types with pervious surface coverage less than 50% are considered as the impervious surface type. Based on the supervise classification tool of RS, the spatial distributions of previous surface type and impervious surface type could be extracted from the RS image. Then, on the basis of the overlaying analysis tool provided by GIS, the area ratios of previous surface type and impervious surface type in each sub-watershed can be calculated by overlaying layer of sub-watershed and the classification results, as shown in Figure 4 and following steps:

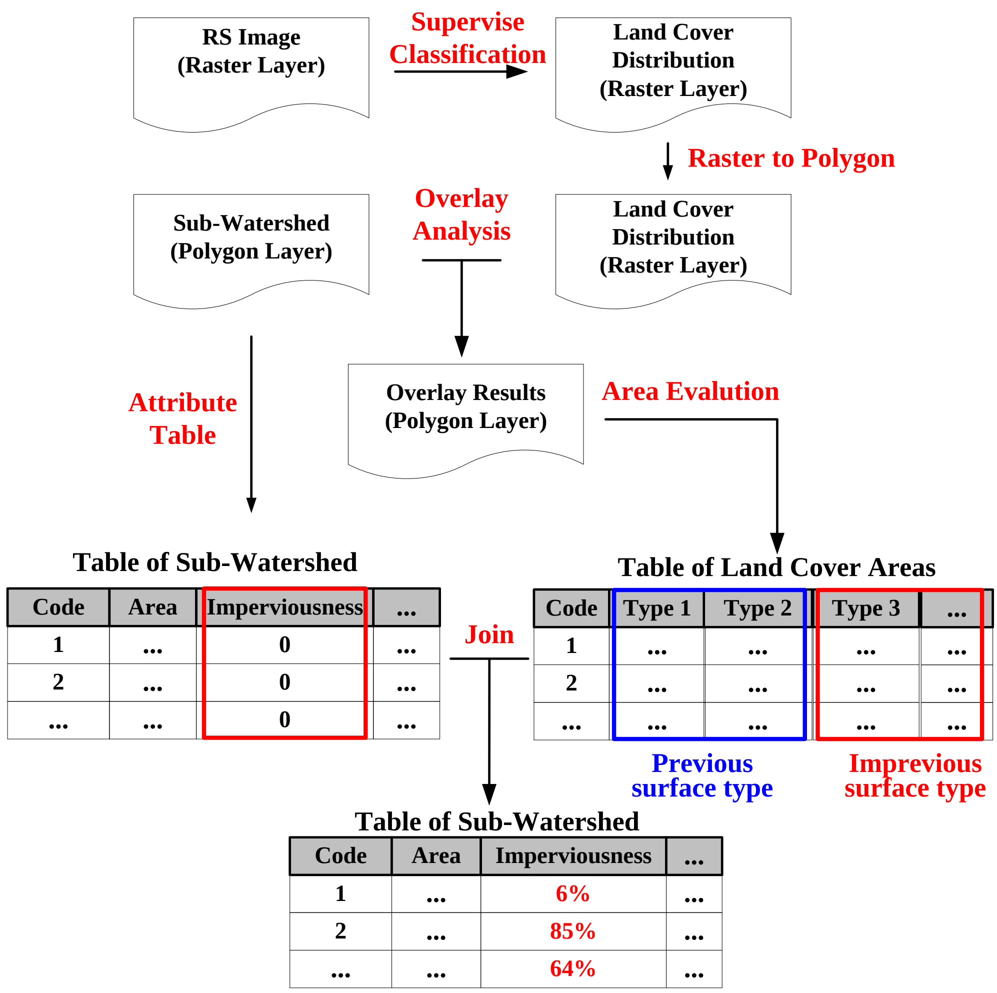

Figure 4. The Processes of Imperviousness Collection for Each Sub-Watershed Based on GIS

1. Obtain the RS image of urban watershed which is stored in the format of raster layer.
2. Gain the spatial distribution of each land cover types in every urban sub-watershed by using the maximum likelihood classification method [15], and store the results as a raster layer.
3. Eliminate the little spot in the results layer, and convert it into polygon feature layer. Each polygon feature in the layer represents one land cover type in the sub-watershed.
4. Convert the layer of classification results and subcatchments into the same coordinate reference system, and then compute a geometric intersection of these two layers by using the intersect tool of GIS, thus get the spatial distribution of land cover types inside each sub-watershed. The results is a new polygon layer which divides the polygon feature of each sub-watershed into several sub-polygon features of different land cover types.
5. Evaluate the area of each sub-polygon feature inside each sub-watershed by using the geometry calculation tool of GIS, and store the results into the attribute table of the new polygon layer according to the code of each sub-watershed.
6. Join the table of new polygon layer to the table of sub-watershed by considering the code of each sub-watershed as the common field, and then the area ratios of previous surface type and impervious surface type in each sub-watershed can be evaluated, thus the imperviousness value of each sub-watershed is obtained.

In summary, the applications of GIS can provide more appropriate data basis and more typical model parameters for the URRS, which can undoubtedly improve the simulation results of the URRS.

4. Visual Displaying of Hydrological Result based on GIS

Similar to data input, the simulation results of URRS are also composed of various kinds of hydrological information. As sub-watersheds are the calculation units of URRS, the results in each sub-watershed are independent, which mainly include the time series of flow rate at the outlet, the flow speed, flow depth in the drainages, the overflow volume from the gullies, and so on. In the traditional data displaying method in URRS, the simulation results are always listed in the statistical table or illustrated in the curves of the hydrological parameters. Those displaying method can provide perfect quantitative descriptions for the simulation results, but their shortcomings in spatial descriptions and analysis are apparent. We can hardly observe and extract the space-time distribution features of the hydrological parameters from the simulation results displayed in the traditional methods. Based on GIS, a new result displaying method is introduced in URRS. In this method, results can be displayed not only in the format of number and character parameters, but also by using spatial distributed maps or process curves.

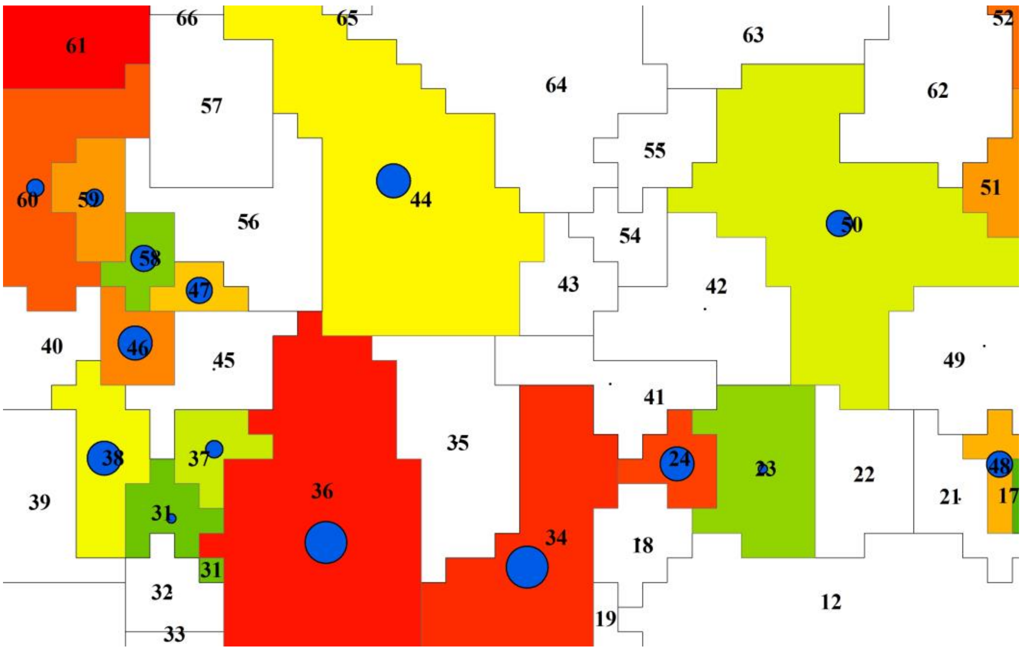

Figure 5. The Water Logging Results that Rendered and Displayed by GIS

On GIS platform, the hydrological result data of each sub-watershed can be stored in the attribute table of dbf file of the sub-watersheds layer. By using graphics rendering function of GIS, the layer of sub-watersheds can be rendered according to one or more hydrological results information inside each sub-watershed. GIS provide different kinds of render methods, such as unique value rendering, classification rendering and charts rendering with pie, column. An appropriate render method can be chosen for each type of hydrological result to describe the hydrological features of it. Take the result of water logging for instance, water logging is the most direct simulation result of URRS and the main data basis of the researches in flood disaster losses assessment. The water logging results of each sub-watershed includes the submerged range and submerged depth, and both of them are rendered by GIS in Figure 4. In Figure 5, submerged range and depth are classification rendered by different colors and symbol sizes, which clearly displays multiple water logging results in one spatial map. For each sub-watershed, redder color means deeper water, and larger symbol size means larger submerged range. The sub-watersheds with no color or symbol inside mean that there is no water logging inside it. As a result, it is obvious that the water logging area is mainly located in the middle south area of the map. The IDs of sub-watersheds that have the largest submerged range are 35, 24 and 36, and the IDS of sub-watersheds with deepest submerged water are 36, 34 and 60.Moreover, detail hydrological information can be obtained by selected any single sub-watershed.

With the application of GIS, the spatial distribution of water logging or any other hydrological results can be displayed directly and accurately in the map, which can provide visualization for the urban flood disaster.

5. Conclusions

In this paper, several applications of GIS in researches of urban storm water management and control are proposed, which integrates the URRS and the spatial advantages of GIS and achieves the effective and scientific data management and organization for the hydrological information from different sources in URRS. The application results show that on the basis of strong spatial analysis, integrative storage and render function of GIS, massive and various kinds of hydrological information from different sources can be organized and managed in reliable and reasonable ways; information from different sources can be integrated or processed in order to meet the requirements of simulation. The applications of GIS can ensure the authenticity and effectiveness of the data input and output of the URRS. Moreover, using the integration ideas and methods in this paper, it is definite that GIS can be applied to the other fields of urban storm water researches such as urban storm risks evaluation or losses assessment, which can enable GIS to play more significant roles in urban flood disaster prevention and control.

Acknowledgements

The authors would like to appreciate the supports for this study from the National Natural Science Foundation of China (no. 41072199 and 41101258) and the National Key Technology R&D Program of China (no. 2008BAC36B01).

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Authors

Ji Shen, he received the B.S. degree from College of Hydropower and Information Engineering, Huazhong University of Science and Technology (HUST), Wuhan, China in 2012. Currently, he is pursuing a PhD degree in Spatial Information Science and Technology at College of Hydropower and Information Engineering, Huazhong University of Science and Technology, Wuhan 430074.

Qiuwen Zhang, he obtained the PhD degree form Institute of Geology, China Earthquake Administration, Beijing, China in 1999. Since 2005, he has been a Professor at College of Hydropower and Information Engineering, Huazhong University of Science and Technology (HUST), Wuhan 430074, China.