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Analysis and evaluation of the effectiveness of Low Impact Development practices on runoff control using Remote Sensing, GIS and hydrological modeling

By

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Abstract

The issues involved in excess runoff caused by urbanization become universal and important environmental and socioeconomic factors around the world. In order to adapt to or mitigate the effect of urbanization on runoff, such as greater runoff volume and peak runoff, expansion and reconstruction of the existing drainage systems and natural water bodies are made in cities, which not only increases the cost of urban development, and runoff loads in downstream cities, but also undermines the existing benign ecosystems. Considering economy, landscape, ecology and sustainable development, several new strategies for urban land development and rainwater management were proposed in developed countries in the 1990s. Low impact development (LID) as representative one of these strategies is applied widely in developed counties.

Study and application on LID practices (LIDs) achieve some results, but still face with many challenges. Due to uneven spatial distribution of climate and spatial variability of underlying surface as well as high monitoring cost, effectiveness data of LIDs is summarized mainly from fields testing and monitoring of urban sites. Lacking application in a large spatial scale area with long-term weather records makes the results of effectiveness evaluation not generalized. Many LIDs are designed and their respective effectiveness is also determined. However, for a mixed land use or land cover (LULC) area with multiple LIDs, the effectiveness in the whole area is still not clearly because of mentioned limitations and the variety of LIDs. In recent years, extreme storms frequently occur in many places of the world, raising the risk of local flooding. LIDs attracts attention in terms of effectiveness evaluation on reducing impacts of the extreme storm, but a debate involved in spatial scale and combined effect of LIDs still has a place. Currently, the conventional method of LIDs designing based on statistical analyzing is still predominant in municipal departments of the developing countries. It is difficult to accurately estimate the effect of urbanization on runoff in a large spatial scale area due to spatial variability. Distributed hydrological models based on computer technologies, integrated with stochastic or determined models are popular in developed countries because of their capacities on reducing the

impacts of spatial variability. However, hydrological models often require a large number of spatial and attribute parameters as input, and are complicated for planners and decision makers. In developing countries, due to the lack of the complete spatial database, low level of data sharing of the local government or municipal departments, and cross-professional conflict, the hydrological modeling method is rarely used. In addition, widespread application of LIDs not only depends on the results of scientific researches, but also support of the government by policy incentives. Due to the lack of effective policy and project incentives, LIDs develop slowly in developing countries. For example, the relatively complete strategy of rainwater management focusing on using LIDs, known as “Sponge City” in China was proposed until 2012.

Current challenges and limitations mentioned above indicate that more studies related to the effectiveness of LIDs should be carried out to supplement the “effectiveness database” of LIDs, especially those involved in the spatial scale, the combined effect of multiple LIDs, and variable conditions such as LULC change and weather/climate change. This dissertation aims to apply an new integrated idea coupling remote sensing (RS), geographic information system (GIS) and hydrological modeling methods based on their respective functional characteristics, to compare and analyze the effectiveness of combined LIDs on regulating runoff volume and peak runoff in a large spatial scale watershed with long-term weather records and multiple LULC types, at the same time, to propose a simple and visualized method for evaluating the performance of combined LIDs to promote understanding of decision makers, and application of LIDs and hydrological modeling methods in China. A watershed in Jinan city of China was selected as the study area which is new as one of the first pilot regions.

Due to the lack of a complete spatial database containing LULC in the study area, Landsat images of the study area in 1979, 1989, 1999, 2009 and 2017 were interpreted and classified to LULC maps, on the basis of using supervised classification method of ENVI, spatial analysis method of ArcGIS, and the map of urban planning. After subcatchment discretization, parameter estimation, and model verifying based on ArcGIS and related mathematical models, SWMM (Storm Water Management Model)

of the study area was built for simulating runoff volume and peak runoff. Importing land use information into SWMM to identify runoff change in response to urbanization of different phases of land development of the study area. The effect of urbanization on runoff volume and peak runoff in the large spatial scale watershed was compared and analyzed. The results show significant changes on runoff of the study area. With the expansion of urban area of the study area, the runoff volume and peak runoff of each subcatchment keeps increasing, which is consistent with the change of urbanization rates of different phases. However, growth rates of some subcatchments decreases after 2009, which might because of the increase of greening area or runoff regulating practices by the local government. The spatial variation of runoff coefficient presents a “Z” shape of “South-North-South”. It indirectly reflects the direction of urban development and construction in the study area over the past three decades. The results not only indicate that runoff change could be as a metric of urbanization, but also serves the layout of combined LIDs.

Urban impervious surface is mainly composed of roof and pavement. Impervious surface is a main source to generate runoff. One of objectives of LIDs is to control the runoff generated from different types of impervious surfaces of different sites from the source, that is, to decentralize the treatment to relieve the processing loads at the end of urban drainage systems. Considering the landscape and costs, three kinds of engineering practices, Rain Garden, Rain Barrel, and Permeable Pavement system were selected as typical representatives of LIDs. According to the input and output path and ratio of treated impervious surface and the characteristics of LIDs, three scenarios with different combinations and layouts of LIDs were established to compare their respective effectiveness on controlling runoff volume and peak runoff. Three scenarios were imported into SWMM for simulation. The results show that same LIDs with different combinations and layouts had significant differences in controlling runoff volume and peak runoff. For controlling runoff volume such as water resources planning, scenario 1 is more effective to achieve this goal. If reducing peak runoff is the target such as urban storm management, scenario 2 is more effective. Taking into account the effectiveness on the ability of controlling runoff and economical efficiency together, scenario 1 could be the most optimal scheme reducing 1m^3 of runoff would cost less. In addition, by analyzing reduction rate of runoff of the whole watershed and subcatchments, the effectiveness of combined LIDs might decrease in the large spatial scale area. By the comparison and analysis, it described how combined LIDs are represented in computational models and compared the effectiveness of combined LIDs in multiple spatial scale.

Extreme weather refers to the occurrence of meteorological events rarely seen in history within a certain period, such as extreme high temperature, extreme drought, and extreme storm. Based on design storm formula of the study area and the Chicago model, several storm events with different return periods and duration were produced. A micro site in a subcatchment with a high runoff coefficient value was selected as the sub study area. Based on the layout of scenario 1, design storm events were imported into SWMM for simulation. The results show that the capacity of combined LIDs for controlling runoff volume and peak runoff is gradually weakened with the increase of storm intensity. Finally, a visualized method based on the seed algorithm, inundation area and 3D scene of GIS was used to evaluate the effect of combined LIDs to provide more intuitive understanding of the effectiveness of LIDs. The visualized performance metric could contribute to increase public awareness and understanding of the LIDs benefits and to make planners and the public to quickly summarize information about the impacts of LIDs on hydrology of a site.

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List of Abbreviations

3D	Three Dimensional
ASCE	American Society of Civil Engineers
BMPs	Best Management Practices
Ci (i=1,2,3..)	The symbol of conduit representing river or pipe
COD	Chemical oxygen demand
CSY.JM	Chengshi Yushui Jinliu Model
DEM	Digital Elevation Model
DLR	Deutsche Zentrum für Luft- und Raumfahrt
DN	Digital Number
ENVI	Environment for Visualizing Images
FAO	Food and Agriculture Organization
FISRWG	Federal Interagency Stream Restoration Working Group (USA)
GDEM	Global Digital Elevation Map
GI	Green Infrastructures
GIS	Geographic Information System
GPS	Global Position System
GS	Grass Swale
GWP	Global Water Partnership
HWSD	Harmonized World Soil Database
IDEAL	Integrated Design, Evaluation and Assessment of Loadings
Ji (i=1,2,3..)	The symbol of junction representing river cross or manhole
LID	Low Impact Development
LIDs	Low Impact Development Practices
L-THIA-LID	Long-term Hydrologic Impact Assessment-Low Impact
LULC	Land use/ Land cover
MOHURD	Ministry of Housing and Urban-Rural Development
MUSIC	Model for Urban Stormwater Improvement Conceptualisation
NASA	National Aeronautics and Space Administration (USA)
NBSPRC	National Bureau of Statistics of the People's Republic of China
NGCC	National Geomatics Center of China
NRC	National Research Council (USA)
P8-UCM	P8 Urban catchment Model
PADEP	Pennsylvania Department of Environmental Protection

PGC	Prince George’s County
PURRS	Probablistic Urban Rainwater and wastewater Reuse Simulator
RS	Remote Sensing
SLAMM	Sea Level Affecting Marshes Model
SPAW	Soil-Plant-Air-Water
Si (i=1,2,3..)	The symbol of subcatchment representing river basin or catchment
SS	Suspended substance
SSCM	Stormwater System Calculation Model
SUDS	Sustainable Urban Drainage System
SUSTAIN	System for Urban Stormwater Treatment and Analysis INtegration
SWAT	Soil and Water Assessment Tool
SWMM	Storm Water Management Model
TN	Total nitrogen
TP	Total phosphorus
TSS	Total soluble solid
UNHSC	University of New Hampshire- Stormwater Center
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VB	Visual Basic
WASP	Water Quality Analysis Simulation Program
WRISD	Water Resources Institute of Shandong (China)
WSUD	Water Sensitive Urban Design
WWHM	Western Washington Hydrology Model

1. Introduction

1.1 Background

Currently, China is in a period of rapid urbanization. This is an inevitable result of industrialization, modernization, and economic growth. However, with the increase of urbanization, problems such as the deterioration of micro-climate environment, intensified flooding risk, increasingly serious runoff pollution, and loss of water resources have become major factors affecting China's sustainable development. The most direct and typical result of urbanization is the change in land use, which in turn has changed the urban hydrological mechanism (Hu et al., 2010). The main manifestation is the increase of impervious surface, which reduces the retention and infiltration of rainwater, resulting in an increase in runoff, and it also brings serious flooding and runoff pollution. Changes in urban hydrological mechanism are mainly reflected in the reduction of groundwater recharge and changes in the volume, peak, duration of runoff and water quality (Sun et al., 2011). For example, the groundwater level in Beijing dropped from an average of about 12m in 1999 to 24m in 2010, forming a depression area of 265,000 ha (NBSPRC, 2012). Changes in urban hydrological mechanism have also led to an acceleration of the confluence process and an increase in hydrological active area. The hydrological active area refers to the area where runoff occurs during the rainfall. Due to urbanization, the loss of vegetation and the reduction of surface retention capacity, hydrological active area shows a significant increase compared to the natural state. The increase in impervious surface reduces the amount of groundwater recharge, increases runoff discharge, reduces Manning coefficient, further shortens the confluence process (Vicars-Groening & Williams, 2007), and increases the frequency of flood peak (Arnold & Gibbons, 1996; Montgomery et al., 1997; White & Greer, 2006).

In order to alleviate the impact of excess urban runoff, conventional rainwater management methods are to extend rainwater pipelines and to construct more rainwater pumping stations so that runoff can be rapidly discharged away. Because of the huge investment in these methods, and the disruption of water quality and ecosystem in receiving water body, rainwater managers begin to stagnate water by draining runoff into centralized detention measures (PA DEP, 2005). However, with the advent of sustainable drainage systems, the disadvantages of centralized retention measures have become increasingly apparent. Discharging runoff into centralized retention measures will reduce groundwater replenishment, increase downstream loads, and threaten the water quality of receiving water bodies (Chen et al., 2013).

With the introduction of low impact development (LID), rainwater management has begun to place emphasis on distributed, small-scale rainwater management measures, as far as possible, reducing the pressure of rainwater runoff to urban drainage system and the impact on the receiving water body through local treatment (PGC, 2000). However, according to current researches, the application of low impact development practices (LIDs) still faces with many challenges. Due to spatial uneven distribution of climate, underlying surface heterogeneity, and monitoring cost constraint, effectiveness data of LIDs mainly comes from monitoring of urban micro spatial scale sites and storm events. The lack of application on a long-term, large spatial scale and mixed LULC (Land Use/Land Cover) makes the result of effectiveness evaluation of LIDs not generalized. Scaling from lot scale to larger scale (e.g., watershed, region) will be a key advancement to evaluate LIDs (Ahiablame et al., 2012). In recent years, extreme storms have frequently occurred in many parts of the world, which has raised the risk of local flooding. LIDs have attracted attention in terms of effectiveness evaluation on extreme storms, but debates involved in scale and combination of LIDs still have a place. In developing countries, due to the lack of complete spatial database, low level of data sharing, lacking government policy and regulations, and project incentives, LIDs have been slowly to develop. In China, due to the late start of related research, although the concept of LID has been sought in the development and construction, due to lacking systematic and scientific rainfall-runoff management methods, the construction of urban rainwater management system is still in the stage of learning and applying foreign experiences.

Hydrological modeling can help to understand and evaluate rainfall-runoff in response to LULC change and LIDs (Tsihrintzis et al., 1998; Lee et al., 2012;Liu et al., 2016). How to formulate the best rainwater management scheme in the new urban planning and design, whether it is in the early stage of project demonstration or the mid-term design and construction, or the later performance evaluation, all need the corresponding models to carry out simulation analysis and use this as a benchmark to conduct design optimization and effectiveness evaluation. In addition, with the development of RS (Remote Sensing) and GIS (Geographic Information System) technologies, more efficient spatial data processing and analysis services have been gradually improved, which are valuable for stakeholders and planners to quickly evaluate and summarize information about the effect of LIDs on hydrology of a site. Therefore, LIDs and computer tools are used to plan rainwater drainage systems in urban areas, and rainwater management measures are systematically laid out in the river basin for rational distribution, so as to mitigate the impact of urbanization on the natural hydrological cycle and threats caused by exceeded runoff. It is of great significance and can provide technical and decision support for urban planners and managers.

1.2 Research objectives and key questions

1.2.1 Research objectives

Current challenges and limitations mentioned above indicate that more studies related to the effectiveness of LIDs should be carried out to supplement the “effectiveness database” of LIDs, especially on multiple spatial scales, combination of LIDs and various environment such as mixed LULC and extreme weather. This dissertation aims to apply an integrated idea combining RS, GIS and hydrological modeling based on their respective functional characteristics to analyze and evaluate the effectiveness of LIDs on runoff controlling at different weather conditions and spatial scales with mixed LULC and multiple LIDs, to promote widespread application of LIDs and hydrological modeling, especially in developing countries like China. The specific objectives are:

1) Based on spatial data processing and spatial analysis of RS and GIS, to build SWMM (Storm Water Management Model) of the study area, describing urbanization effect on runoff, and effectiveness of LIDs by computational modeling.

2) To identify runoff response to urbanization of different phases of land development and examine impacts of urbanization on runoff volume and peak runoff in the study

watershed with a mixed LULC and long-term rainfall records.

3) To compare and analyze the effectiveness of combined LIDs in different design scenarios at the watershed scale and long-term climate condition, to highlight evidence of hydrological benefits of LIDs, providing technical and decision support for urban planners and managers.

4) To compare and analyze the effectiveness of LIDs encountering extreme storms, with a visualized performance metric, which contributes to increase public awareness and understanding of LIDs benefits and the implementation of LIDs. To suggest opportunities for research and development of decision support tools incorporating LIDs, making stakeholders and planners to quickly evaluate and summarize information about the effect of LIDs on hydrology of a site.

1.2.2 Research questions

In this context, the main challenge of this study is to better understand urbanization effect on runoff and LIDs effectiveness at various spatial-temporal scales, to provide decision support for the formulation of future urban planning and decision making. Under this challenge, the following questions are raised and need to be answered:

1) How to determine the value of input parameters of Storm Water Management Model and how is to use this model in the absence of a completed spatial database?

2) How to describe the process of urbanization in the context of application of Storm Water Management Model?

3) How is the effectiveness of combined Low Impact Development Practices in a large area in relationship to extreme storm conditions?

4) How to weaken the impact of heterogeneity of weather and underlying surface in a large area?

5) How to make planners and decision makers more intuitively and quickly to obtain information of hydrology characteristics and efficiency of Low Impact Development Practices?

1.3 Organization of the dissertation

This dissertation consists of six chapters. After the introduction provided in this chapter, a theoretical background for this study is introduced in chapter 2. First, it provides the conceptual basis in the context of natural hydrological cycle and urbanization effect, urban rainwater management, LIDs and rainfall-runoff modeling. Following the theory and history of related approaches and their strengths and limitations are also introduced. Chapter 3 is concerned with the study area of Jinan city, China. After having established the theoretical framework, current water risks in China and the geographic characteristics of Jinan are introduced in the national context of China. Furthermore, a spatial database for this study is described, which includes GIS data, Remote Sensing data as well as other data. Chapter 4 focuses on methodology in this study, presenting the methods used for building SWMM used to evaluate the effectiveness of LIDs at watershed scale and long-term weather condition and extreme storm events, exploring an improved method based on inundated area and 3D (three dimensional) scene to evaluate LIDs. Chapter 5 presents and discusses the findings generated by the methods in chapter 4. In addition, some implications of urban development in Jinan are given. In chapter 6, finally, answers to the research questions proposed in chapter 1 and major findings are provided. Based on the study findings, the development recommendations and the future work are also presented.

2. Theoretical background

2.1 Conceptual basis

2.1.1 Natural hydrological cycle and urbanization effect

Natural hydrological cycle is the process by which water reaches the surface through atmospheric precipitation and other activities, then enters the ocean through runoff, and finally returns to the atmosphere. The whole process includes the processes of precipitation, interception, runoff, infiltration, and evaporation (NRC, 1991). When the rain falls to the surface, it is first intercepted by vegetation, part of the rainwater is stored in the underlying surface, part of the rainwater seeps into the ground, and part of it is discharged into rivers and eventually into the ocean system. Some of the precipitation stored by the vegetation eventually enters the atmosphere through evaporation. The precipitation stored in the depression is evaporated into the atmosphere or infiltrated into the ground. The infiltrated water will re-enter the surface soil, then be used by the plants or contribute to the underground water layer (Chin et al., 2000). Research shows that about 40% of precipitation is intercepted by vegetation and stored in natural landscape water. The intercepted precipitation will eventually return to the atmosphere through evaporation and transpiration. About 25% of the precipitation will go deep into the ground, forming a sub-layer or underflow back into the stream, and the other 25% of the precipitation seeping into the ground to form groundwater. Another 10% of precipitation forms surface runoff (FISRWG, 1998).

With the development of society, human beings have gradually gathered in cities, concentratedly built production and living facilities, and completely changed the morphological characteristics of these regions, thereby affecting the natural hydrological cycle and forming an urbanization system different from the natural state (Dion, 1993). Urbanization and urban expansion transform natural land into a development area that can support the needs of urban life. After urbanization, the underlying surface is hardened, and the original vegetation and soil are replaced by impervious surfaces, reducing the surface water intake and the amount of water intercepted by vegetation. Affected by factors such as water imperviousness, stagnant water space, drainage pipe network and river channels, production and confluence parameters such as surface runoff and confluence time have changed, and runoff and confluence time have been shortened, and flood peak has increased in advance. Figure 2-1 shows the changes in the hydrological cycle before and after urbanization.

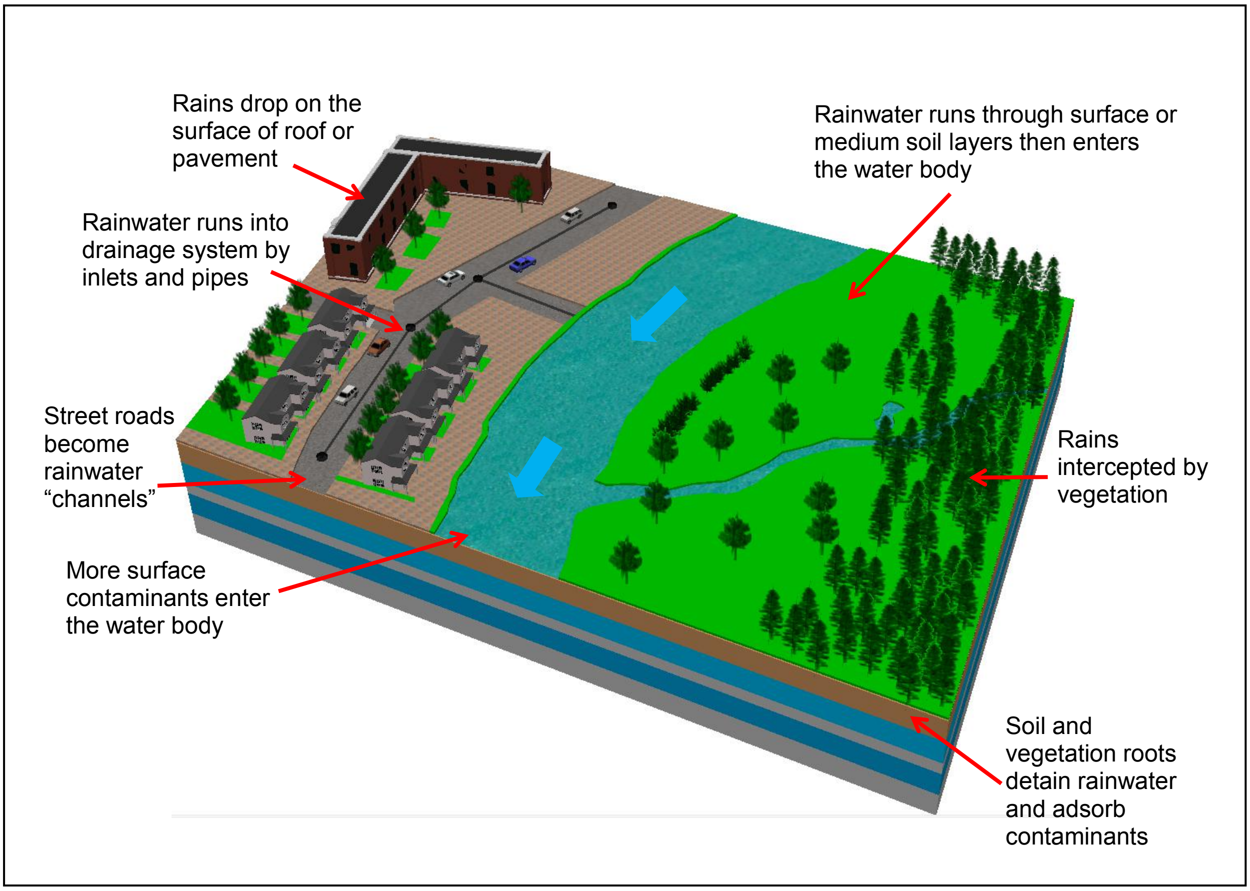


Figure 2-1: Urbanization effect on natural hydrological cycle (Source:City of Blue Springs)

The main manifestation of urban expansion is the continuous decline in the percentage of pervious surface, which has changed the original natural hydrological cycle in the region. It mainly affects the regional hydrological status in the following aspects:

1) The influence of urbanization on runoff

At the same time as urban sprawl, the natural hydrological cycle is disturbed in many ways. Due to the increase in impervious area and the compaction and hardening of the soil resulting in decrease in the amount of percolation, increase in runoff, and decrease in the amount of savings in the depression. The decrease in trees and vegetation causes decrease in evaporation. The increase in impervious area and the reduction of effective rainwater storage system lead to reduction in the time for runoff. The decrease in groundwater recharge due to the increase in impervious area and the reduction in the amount of infiltration. The lack of base flow leads to decline in the flow of rivers and lakes during the dry season. The increase in runoff leads to the widening of downstream channels (ASCE, 1998; USEPA, 2002; Arnold et al., 1996). Research shows that in a highly urbanized area (more than 75% of impervious area), about 30% of precipitation returns to the atmosphere through evaporation, 10% of precipitation will infiltrate the ground, 5% of precipitation will penetrate into the ground, 55% of precipitation directly forms runoff (Arnold et al., 1996). The US Environmental Protection Agency (USEPA) also found that the ratio of runoff to rainfall (defined as the runoff coefficient) is usually directly proportional to the degree of imperviousness (USEPA, 1983). According to the study of Espey et al.(1968), the peak discharge in urbanized area is 3 times before urbanization in this area, the peak time is reduced by 1/3, and the storm runoff volume is 2~4 times before urbanization. Figure 2-2 shows the change of peak in some area before and after urbanization. After urbanization, the flood peak increased significantly, and the time for flood peak occurrence was greatly advanced.

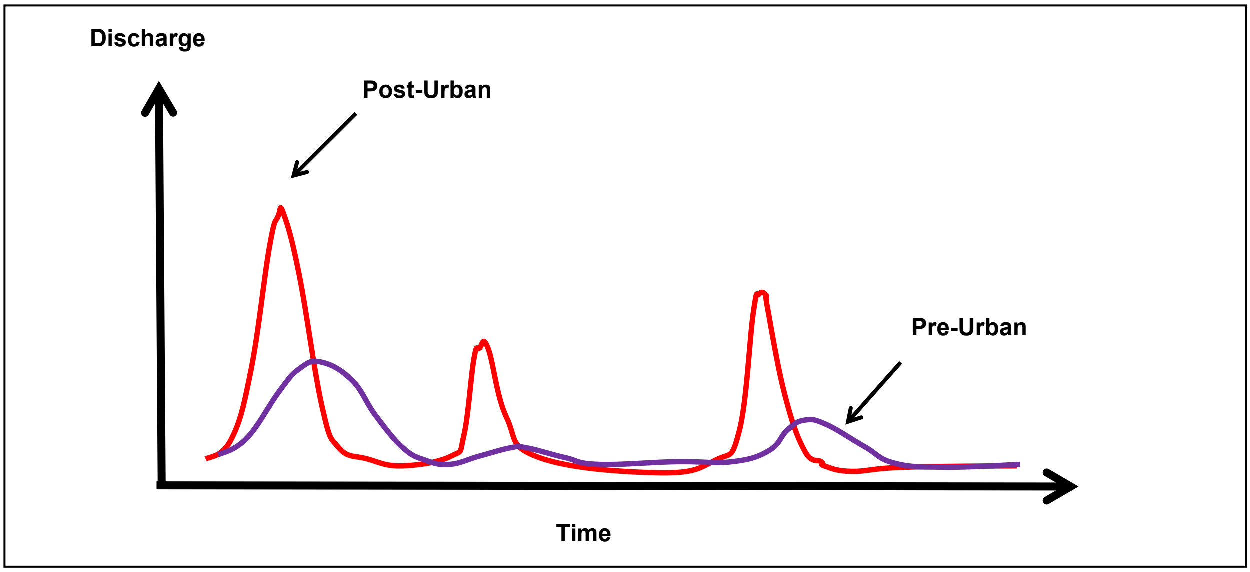


Figure 2-2: Runoff change before and after urbanization (Source: Chen, 2013)

2) The influence of urbanization on water quality

After urbanization, pollutants generated and emitted from human activities are significantly increased, and the types of pollutants are increasingly complex and diverse. The transmission of ground pollutants to the downstream water through the action of urban runoff, such as erosion and dissolution, will cause the water quality of the receiving water bodies to deteriorate. Urbanization increases the impervious area in urban area, while increasing soil erosion and sand production (USEPA, 2002). The most common pollutants in urban runoff include: sediments, bacteria, nutrients, toxic chemicals and other pollutants (Adams et al., 2000; USEPA, 1984). In the United States, the National Urban Runoff Program monitored harmful emissions from 28 cities from 1978 to 1983, where urban runoff had high sand production, high bacterial concentrations and high heavy metal concentrations (Field et al., 1993; Vorreiter et al., 1994), runoff carrying pollutants caused 1/3 to 1/2 rivers to be contaminated (USEPA, 2000). In the USEPA's biennial national water quality inventory report, urban runoff or stormwater are evaluated as the third or fourth largest source of pollution for river courses and streams (USEPA, 2007; USEPA, 2009; USEPA, 2005). In the study of runoff in China, Xu et al. (2009) used Remote Sensing and GIS to analyze the hydrological effect of urbanization in the Yangtze River Delta. It was found that with the rapid development of urbanization, the water purification capacity of the watershed in the river basin dropped drastically, and river water quality deteriorated. In terms of the impact of urbanization on water quality, research abroad has been more in-depth, mainly focusing on the accumulation and eutrophication of nitrogen and phosphorus nutrients (Varis et al., 1997; Eshelman, 1991), the impact of heavy metals on water ecosystems (Pouyat et al., 2007; Chang et al., 2004; Bannerman et al., 1993) and the increase sedimentation in volume (Nelson et al., 2002) and so on.

3) The ecological effect of urbanization on water bodies

In urbanization, the increase in water impermeability directly leads to increase in surface runoff and reduction in groundwater recharge. Changes in surface runoff volume, peak and duration are the main causes of ecological damage to downstream receiving water bodies (Fitzpatrick et al., 2005; Nelson et al., 2007; Walton et al., 2007). In addition, due to the increase of impervious area, the surface with natural planting of the vegetation is changed to impervious surface, the vegetation coverage is reduced, the removal of pollutants and the interception effect are reduced, a large number of sediments and pollutants accumulated into the receiving water bodies inflict impact on ecosystem and disrupt the ecological balance of the receiving water bodies

(Carle et al., 2005; Greer et al., 2003).

2.1.2 Urban rainwater management

Before the Second World War, sewage and rainwater flowed into the receiving water bodies in confluent manner. The combined drainage system has negative impact on the residents living downstream and the environment. Since the 1960s, sewage treatment plant has been used. Waste water and rainwater have been transported separately in different drainage channels. Municipal sewage is discharged into sewage treatment plant, and urban rainwater is directly discharged into rivers, lakes, and other water bodies (Debo et al., 2010). Diverting drainage system can effectively discharge the rainwater into the water bodies at the time, alleviating the local flood problem. In 1973, the United States enacted the 'The Clean Water Act', which published a series of regulations concerning the detention of rainwater (USEPA, 1999). According to the regulations, some areas have developed large-scale rainwater depressions to control the peak of rainfall. Although they can directly and effectively resist flood peak through detention function, they have no obvious effect on reducing flood peak in the downstream area.

At the end of the 20th century, under the guidance of the concept of sustainable development, a new concept of sustainable urban rainwater management emerged. The Global Water Partnership (GWP) summarized the integrated management of rainwater resources into a process that promotes water, land, and related issues. The coordinated development and management of resources maximizes the economic and social benefits obtained in a balanced manner without compromising the sustainable development of ecosystems (Stålnacke et al., 2010). Under the concept of sustainable rainwater management, researchers from many countries have developed many new technologies, such as Best Management Practices (BMPs), Water Sensitive Urban Design (WSUD), Sustainable Urban Drainage System (SUDS), and Low Impact Development practices (LIDs), Green Infrastructures (GI), etc. (PGC, 1999; Charlesworth et al., 2003). These concepts and technologies are expressed in a variety of ways, but the core is to scientifically and systematically design, construct, operate, and manage urban rainwater system, strive to control increased urban runoff, control the emissions of non-point source pollutants (Wang et al., 2003). Among these new types of urban rainwater management concepts, BMPs and the later proposed LIDs are the most representative and are widely used in urban construction. BMPs aim to manage rainwater based on the end-control method to achieve peak control, runoff volume control, and pollutant control. LIDs focus on source-control to regulate runoff and improve urban rainwater usage.

2.1.3 Low impact development practices (LIDs)

Low impact development (LID) is a new rainwater management concept proposed by the Environmental Resources Agency of Prince George County, Maryland, in the mid-1990s. The LID mainly advocates the use of decentralized small-scale rainwater treatment facilities or practices (LIDs) based on micro-scale landscape control, so that the hydrological characteristics after development in the region are basically same as those before development, and the impact of regional development on the surrounding ecological environment is minimized, and a site with good hydrological function is constructed (USEPA, 2000). At present, typical LIDs are summarized in Figure 2-3:

Rain Garden/Bioretention is depression that contains vegetation grown in an engineered soil mixture placed above a gravel drainage bed. It provides storage, infiltration and evaporation of both direct rainfall and runoff captured from surrounding areas.

Green Roof is another variation of Bioretention cell that has a soil layer laying atop a special drainage mat material that conveys excess percolated rainfall off of the roof.

Infiltration Trench is narrow ditch filled with gravel that intercept runoff from upslope impervious areas. It provides storage volume and additional time for captured runoff to infiltrate the native soil below.

Permeable Pavement is excavated area filled with gravel and paved over with porous concrete or asphalt or paver block to make the rainwater infiltrate at natural rates into the site's native soil.

Rain Barrel (or Cistern) is container that collects roof runoff during storm events and can either release or re-use the rainwater during dry periods.

Vegetative Swale is channel or depressed area with sloping sides covered with grass and other vegetation. It slows down the conveyance of collected runoff and allows it more time to infiltrate the native soil beneath it.

Figure 2-3: Typical LIDs (USEPA, 2015)

As a simple, efficient and landscaped ecological rainwater management approach, LIDs have the following 6 typical characteristics.

1) Flexible: first, almost any form of landscape (building, road, planter, etc.) can be used for LIDs with some degree of improvement and used to control and process rainfall-runoff (Peter, 1999). Secondly, compared to traditional rainwater management methods, LIDs are suitable for more types of rainfall, especially for small and medium-sized rainfall. The design of traditional development is often based on rainfall events, while design of LIDs uses distributed small-scale landscape measures, which play a role in the first time rainfall to runoff. The rainfall runoff from the site has been built from scratch. It is managed under the full influence of LIDs (USEPA, 2007).

In addition, LIDs are suitable for most new construction and renovation projects. Combined with a certain site design, LIDs can be a powerful tool for protecting and restoring the ecological environment. In undeveloped areas, LIDs can be used as a means to ensure that the developed site maintains its pre-development hydrological conditions. In areas that have been developed and are under development, LIDs can be used to reduce the impact of existing development models on the receiving water bodies and the surrounding natural environment.

2) Multifunctional: multiple types of LIDs have additive effects, and multiple types determine multi-function. LIDs reduce rainfall runoff by promoting rainwater infiltration, transpiration, or harvesting irrigation to bring the developed hydrological conditions closer to or prior to pre-development, minimizing the impact of development.

3) Economical: whether in terms of construction or maintenance, LIDs save costs compared to conventional rainwater management models (Peter et al., 1999). Since the flow control of LIDs is achieved through permeation and transpiration, the cost savings are mainly reflected in the reduction of the use of rainwater pipe network systems and other underground infrastructures. Moreover, according to some experiences, the cost of waste water treatment is much higher than the cost of protecting the water body. Because rainwater can be filtered and filtered by LIDs, LIDs can indirectly reduce waste water treatment costs.

4) Paying attention to protection: LIDs are mainly used to protect more sensitive open spaces and control impervious areas in development sites. Protecting open spaces can control development activities to a certain extent, thereby reducing the occurrence of rainfall runoff.

5) Source control: LIDs use landscape design to manage the rainwater when it falls to the ground, focusing more on restoring rainwater management capabilities to the natural state before development.

6) Natural effect: LIDs mainly simulate natural processes through the following mechanisms, and ultimately achieve the purpose of managing rainfall runoff. Promoting interception, infiltration and evapotranspiration, increasing sediment removal, filtration and evaporation efficiency, increasing soil stability to reduce soil settlement and soil

erosion, increasing adsorption, ion exchange and organic synthesis, accelerating transpiration, nutrient cycling, bio-absorption and microbial decomposition (Coffman et al., 2001).

The main objective of LIDs is to maintain or restore the hydrological mechanism before site development. It is mainly reflected in the volume, peak and duration of runoff. It has a complex form and involves many aspects of runoff. LIDs mainly achieve the goal of restoring the hydrological mechanism under natural conditions through the following technical systems (USEPA, 2009).

1) Minimize the impact of runoff in the city. The existing LIDs mainly include reducing impervious areas in cities, protecting natural resources and ecological environments, maintaining natural drainage channels, and reducing the use of drainage pipelines. Studies have shown that the increase in urban impervious area is the most important cause of changes in the hydrological cycle mechanism. Therefore, reducing the proportion of impervious area in urban areas can increase the infiltration of groundwater by runoff and change the runoff path, thereby managing rainwater resources in terms of runoff volume, peak, and duration.

2) Through a series of runoff control measures, the runoff is evenly distributed throughout the area, its concentration is reduced, the time of confluence under natural conditions is maintained, and excretion is regulated. Runoff in the natural state is in a distributed state. Part of the precipitation directly infiltrate the groundwater, while the other part forms runoff, and the confluence takes a long time. Through a series of interception and retention measures, LIDs increase the infiltration of groundwater and extend the confluence time while extending the runoff path. These distributed control measures can evenly distribute the runoff throughout the entire region, reducing the concentration of runoff, reducing the peak flow, and increasing the time of confluence, thus restoring the natural hydrological cycle mechanism in terms of magnitude, frequency, and time of runoff.

3) Implement effective public training, encourage landowners to use pollution control measures, and protect existing land landscapes with hydrological control functions. Through public efforts, these measures encourage the protection of land landscapes

with functions of hydrological regulation so as to realize the regulation of runoff by land landscapes.

LIDs are not only an abbreviation for a series of rainwater management measures, but also new design concepts. They integrate economic, environmental, and development elements and are design strategies based on economic, ecological, and sustainable development. According to the recommendation of the LID Research Center of the United States, the design concept of LID includes the following aspects (USEPA, 2000).

- To provide advanced technologies and effective economic mechanisms for the ecological protection of surface water bodies.
- To introduce new concepts, technologies and goals for rainwater management, such as the microscopic and functional aspects of the land landscape, minimize the impact of changes in hydrological mechanisms on the regional ecological environment, or restore hydrological mechanisms in the natural state, and maintain the integrity of regional biological species to improve the development of ecologically functional rainwater management measures.
- To discuss the rationality of rainwater management measures and other control measures from the aspects of economy, ecological environment and technical feasibility.
- To promote public participation in ecological environment education and protection.

As new types of rainwater management measures, the designs of LIDs also vary from place to place. According to the view of Prince of Georgia in the United States, the designs of LIDs should follow the following principles:

- Making overall framework based on local hydrological characteristics
- Designing based distributed ideas
- Controlling from the source
- Adopting convenient design methods
- Building a versatile land landscape

At present, the use of monitoring data is the most widely used method for evaluating the performance of LIDs application. It mainly uses samples before and after LIDs processing for comparative analysis. The methods for evaluating LIDs performance mainly include:

1) Field survey: it is a simple observation of LIDs, such as the depth of stagnant water in a Bioretention or a Green Roof. At the same time, the field survey can also provide the intuitive operation status of the inlet and outlet measures, the growth of the vegetation, and the hydraulic problems of the soil textures.

2) Infiltration performance and runoff test: through a series of tests to determine the saturation infiltration rates of LIDs. For example, artificial rain is used to measure the LIDs effectiveness.

3) Monitoring: monitoring LIDs is often difficult because monitoring requires not only a great deal of time and effort, but also the uncertainty of the results will affect the effectiveness of the monitoring. For example, a typical monitoring cost of 1-2 years almost exceeds the cost of building a small biological retention pool. Therefore, choosing the right technology for performance monitoring is the key to the current research. Research on water quality and hydrological performance monitoring are mainly based on sampling and experimental methods. LIDs long-term monitoring data for performance evaluation studies is still rare. On the one hand, the cost of long-term monitoring is too high. On the other hand, LIDs just begin to be implemented in some countries. Therefore, whether LIDs can truly achieve the protection of the ecological environment, and its performance monitoring still needs in-depth research.

Because the long-term monitoring data in the field is not easy to obtain, the long-term performance of LIDs simulation has become a research trend. The model for evaluating LIDs performance must accurately represent the actual situation before and after the development of regional urbanization. At present, only a small number of models can simulate the hydrological mechanisms before and after the regional development. Because it is difficult to verify the pre-development LIDs, the LIDs simulation requires a mechanism model that can pre-estimate the parameters. In addition, the model must also be able to perform long-sequence analysis and apply to specific time intervals. In the area before development and design of LIDs, the model must also be able to simulate inflow infiltration and groundwater movement, so as to accurately estimate the soil moisture content. Due to the wide distribution of LIDs, it requires higher accuracy than other runoff simulation models. Since the runoff often flows from the impervious area to the permeable area or from the permeable area to the impervious area, the frequent change of the nature of the land use requires the model to simulate the runoff well. At present, SWMM (Storm Water Management Model), SUSTAIN (System for Urban Stormwater Treatment and Analysis INtegration) and L-THIA-LID (Long-term Hydrologic Impact Assessment-Low Impact Development) model are the most commonly used models for LIDs, and SWMM is the most widely used.

The development of any new kind of thing must be accompanied by its advantages and limitations. Its advantages will keep this new thing moving forward, and while limitations limiting its development also breed new breakthroughs, and LIDs are no exception. The ecological environmental protection function is the most significant advantage of LIDs. Since the 1990s, due to changes in the hydrological mechanisms caused by urbanization, the deterioration of the urban ecological environment has become a consensus. Therefore, people begins to discuss rainwater management measures that can restore the natural state of the hydrological mechanisms, and LIDs in the background come into being. Today, most of the developing regions are faced with the problem of urban expansion. The expansion of the city takes up a lot of green spaces, such as grasslands and forests. At the same time, the expanding urban areas also increase the pressure on ecologically sensitive areas. LIDs emphasize the protection of the ecological environment. At the same time, LIDs also offer the possibility of pollution control in urban areas. In general, for developed cities, LIDs can reduce the impervious ratio of cities through Bioretention, Green Roofs, etc.. For developing cities, LIDs emphasize the protection of green areas and advocate the use of natural drainage patterns. LIDs integrate with local development policies to realize development while achieving protection of the ecological environment and causing minor disturbances to the hydrological mechanisms in the natural state, thereby realizing a truly low impact development. Compared with conventional rainwater management measures, LIDs have unparalleled advantages in terms of ecological environmental protection. In addition, LIDs cost less, and low cost is not only important for the construction of rainwater control projects, but also for long-term maintenance and plays an important role on the entire cycle.

Although LIDs have many advantages such as ecological environment protection, but with the gradual deepening of LIDs research, people are gradually aware of the limitations of LIDs. According to a comprehensive analysis of existing LID literature, LIDs are mainly limited by design issues, climate factors, policies and regulations, public training, maintenance, and cost calculations. Among them, the design problem is the most important one of LIDs limitations, mainly including the following two aspects. 1) What are the most economical and most reasonable LIDs to achieve such goals as rainwater management or water quality control? 2) How to determine the elements of the selected LIDs, and the elements relate to many factors such as climatic factors, topographic conditions, soil elements, and model simulations in the study area. In addition, since LIDs are a series of new concepts and measures, local policies and regulations may contradict the implementation principle of LIDs, and these policies and regulations will directly limit the development of LIDs. In addition, people know very little about LIDs, so public training and LIDs maintenance and management are also major issues. Currently, there is a lack of effective cost calculation data and calculation tools for the service life of LIDs, which limits the effective analysis of LIDs costs and benefits, and cost-benefit analysis can enhance people's confidence and determination to implement LIDs. In China, for many urban planners or landscape designers, LIDs are a brand-new ideas and technologies, but LIDs have been practiced in many countries in Europe and America for many years, and have achieved fruitful results accordingly. LIDs have become an indispensable part of the construction of “Low-Carbon Eco-city” and “Green City” due to their significant benefits in the areas of rainwater runoff pollution, hydrological cycle rehabilitation, and flood volume and peak controlling. It is of great strategic significance to meet the needs of the people's livelihood and promote the sustainable development of the economy and society.

2.1.4 Rainfall- runoff modeling

Urbanization leads to change in the condition of the site's underlying surface, which in turn changes the characteristics of local runoff generation and distribution. Some studies have pointed out that the annual total runoff increases with the impervious area, the total annual rainfall runoff in a fully urbanized area is 4-5 times that of a similar natural watershed (Liu et al., 2009), and the peak is 10 times higher (Fang, 2001). The main reason is that urbanization reduces the interception and infiltration capacity of rainwater at the surface, resulting in the transformation of urban drainage system from the original surface ditches and rivers and lakes into complex underground pipe networks (Zhao et al., 2008). In order to understand the urban rainfall runoff process in depth, the urban rainwater models emerge and develop rapidly.

The urbanization of developed countries is earlier, and there are more studies on storm disasters. Since the 1960s, rainfall-runoff models that meet the requirements of urban drainage design and flood control have been developed, and accurate and real-time rainfall-runoff warning systems begun to be established. With different application purposes and requirements, corresponding rainfall-runoff models have been developed to analyze flooding disasters, and played an important role in urban storm management, pipe network design, flooding prevention and drainage, flood risk analysis, etc. (Christopher, 2001; Elliott et al., 2007; Xie et al., 2005). At present, the widely used rainfall-runoff models abroad include: SWMM, InfoWorks-ICM, and Mike-Urban. The development of computer technology has accelerated the development and application of these models. The application and development history of mathematical modeling technology in urban area are also demonstrated, but at the same time it also exposes many deficiencies, namely that these rainfall-runoff models generally lack the reliability analysis, risk assessment, and economic analysis functions of urabn drainage systems. The focus of development should be on integrating these modules into the rainfall-runoff models.

In China, the research on rainfall-runoff modeling is still in its infancy. At present, there is no general urban hydrology and water quality model with multiple functions. Only some achievements on the basis of absorbing foreign research results have been achieved. For example, in 1993, China’s first self-developed and relatively complete urban rainwater pipe calculation model (SSCM) (Cen et al., 1993) was proposed by Cen Guoping. In 1997, Liu (1997) focused on SWMM based on the characteristics of runoff generation and convergence of China’s urbanized areas to establish an urban drainage network model. In 1998, Zhou et al.(1999) established urban stormwater runoff model (CSY.JM) for designing, simulating and analyzing drainage network. In 2000, Chou et al.(2000) combined simulation technology with urban weather forecast monitoring technology to establish a storm flooding simulation model of Tianjin. In 2001, Zhou et al.(2001) used VB and FoxPro as tools to develop an unsteady flow simulation model of urban drainage system.

In recent years, with the application of 3S (RS, GIS and GPS) technology in hydraulic engineering, environmental protection, and urban construction, China has successively developed some 3S-based rainfall-runoff models (Bai, 2001). The rainfall-runoff models based on one-dimensional and two-dimensional unsteady flow equations have been successfully applied in first-tier cities such as Tianjin, Shanghai, Shenzhen and Beijing. The study of these models has promoted the study of urban rainfall runoff in China, but compared with foreign models, there is still a big gap between the rainwater flooding models developed in China. The models developed in China are generally only suitable for urban drainage, flood control and other calculations, there is no water quality simulation module. Many models in foreign countries have both water quality and water quantity simulation capabilities. The main problems of rainfall-runoff modeling in China are concentrated in the following: 1) Models are built for specific research areas, lacking pre-processing and post-processing functions, and are not visualized and operable. Foreign models can be widely used in planning, design, and management work in different regions, and the model has strong functions before and after processing. The data analysis and management capabilities are strong and the degree of visualization is high. 2) Insufficient basic research on the value range of models parameters. 3) The situation of urban drainage systems in China is complex. The establishment of a rainfall-runoff model requires comprehensive consideration of the coexistence of multiple drainage systems, the characteristics of pumping systems, mutual connectivity between systems, the infiltration of groundwater into groundwater, and the deposition problem of flat terrain. 4) Lacking detailed and sub-scale rainfall or runoff measured data as a basis for calibration and verification. Therefore, in the future, the research of rainfall-runoff modeling in China will mainly face three tasks: 1) To integrate with the international research frontier and form certain advantages in certain fields. 2) Based on the mature models of foreign countries to modify and improve according to the actual conditions in China so that it can be effectively used for rainwater management in China. 3) To conduct some basic work such as a general survey of rainfall and runoff data on typical underlying surfaces of cities as modeling inputs.

2.2 Evaluation of typical LIDs based on laboratory study

2.2.1 Grass Swale

Grass Swale is usually used as transported facility for runoff of pavement. It is generally built along the streets of residential areas and along the roads. It can be improved according to actual conditions. Based on the transmission method of surface runoff, Grass Swale is divided into three types: standard conveyance swale, dry swale and wet swale. Dry swale can be used to increase the penetration of rainwater from both quality and quantity. Wet swale uses dwell time and natural growth to reduce peak discharge and treat rainwater before it enters the downstream area. Wet swale has resistant plants that can grow permanently in standing water and is suitable for use in highway design (USEPA, 1993).

Grass swale can retain more than 93% of SS in rainwater runoff (Singhal et al., 2008), reduces organic pollutants, and removes some metal ions and oils such as Pb, Zn, Cu, and Al. Since there is a good correlation between SS and COD, TP, TN, and other pollution indicators in urban runoff, other pollutants will be removed when SS has a higher removal rate (Zhang et al., 2003). Deletic and Fletcher (2006) show that the retention rate of TSS in GS is 61-86%, the TN removal rate is 46%, and the TP removal rate is 56%. However, the water quality in the study area is not stable. In the study by Stagge and Davis (2006), the removal rate of TSS by GS is 65-71%, and the removal rate of Zn is 30-60%. In general, the removal rate of pollutants in dry swale is significantly better than that of standard conveyance swale and wet swale. Standard conveyance swale has higher removal of heavy metals than wet swale, and wet swale has soluble phosphorus release, but the reasons are not yet clear (Liu et al. 2008).

Grass Swale can be adapted to a variety of environments, and is highly versatile in design and relatively low in cost (Dorman et al., 1996). Small drainage areas with gentle slopes are more effective. Grass Swale on the roadside can replace conventional gutter and curb. Due to the visible pollutants in Grass Swale, Grass Swale can replace conventional underground drainage system, which can fundamentally solve the problems of mixing and connecting the rainwater and sewage pipelines, effectively controlling and handling the runoff transmission process and contaminants entering the receiving water bodies.

2.2.2 Green Roof

Studies have shown that roofs as impervious surfaces can reach 40-50% of the total area of impervious surfaces in cities (Dunnett et al., 2004). Especially in the old cities, towns generally still use backward combined drainage systems, which makes the overflow problem more serious. By reducing the impervious area of the city, it is very effective in reducing storm flooding. Therefore, if these roofs can be effectively used in cities, they will have very significant results. In some highly urbanized countries such as Germany, Japan, Singapore, Belgium, the government encourages the application of roof greening and has formulated some incentive policies and even forced some projects to apply this technology, resulting in very good results (Dunnett et al., 2004; Osmundson, 1999; Wong et al., 2003). Green Roof technology in Germany has a history of several decades of development, and has a large number of research data and successful cases.

Green Roof is very effective in reducing rainfall runoff. A simple Green Roof in temperate region, about 80mm thickness structure, can reduce 50% of annual runoff (Miller, 2000). German researches show that 80mm design is most cost-effective. Reasonable design can not only reduce runoff, but also build vegetation on existing roofs without additional facilities. When applying Green Roof, special consideration should be given to the overflow problem of combined drainage systems and hydrodynamic loading problems. In the city of Leuven in Beigium, A roof with a slope of 20° was observed. In the process of a continuous 24 hours (April 2003, first day 5 pm to next day 5 pm) rainfall reached 14.6mm. The difference in rainwater retention on conventional roof and Green Roof is obvious (shown in Figure 2-4) (Mentens et al., 2006).

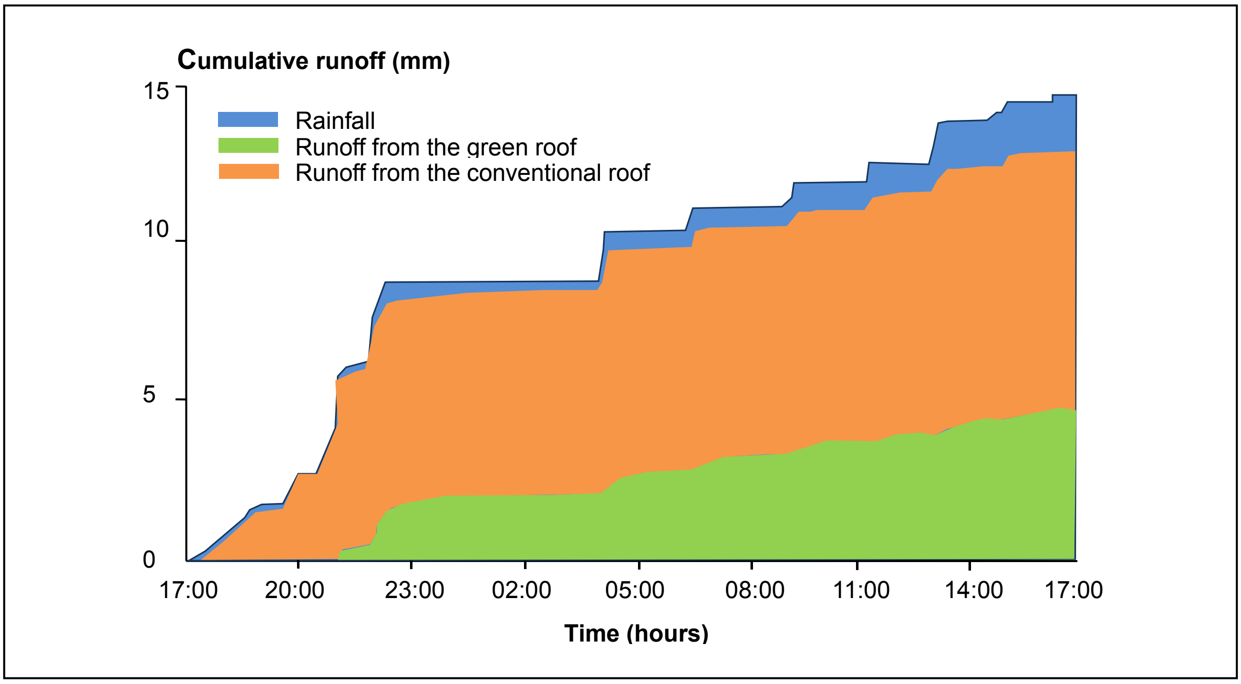


Figure 2-4: Difference in runoff from conventional roof and Green Roof

Rainfall retention on Green Roof is achieved through the storage of media and the evaporation of plants. Rainfall retention rate for Green Roof in different regions is around 60-70% with an average of about 63% (Table 2-1). The research on Green Roof is generally performed on different thicknesses of soil layers, and slopes of different degrees are analyzed. Although the increase of the medium thickness and the reduction of the roof slope can increase the retention, it is not significant. Generally, the thickness of the medium is 2-12cm. There will not be a significant amount of stagnation (Table 2-1). This means that in order to reduce construction costs and the need for structure, even a thin medium is acceptable for specific rainfall retention needs. However, for Canada Investigations in the province of Ontario have found that about 5 cm of medium is more likely to cause frostbite perennials in winter than 10-15 cm (Boivin et al., 2001). Sedum spp. is a typical species in Green Roof due to drought tolerance. Although Boivin et al. (2001) did not examine Sedum spp., other researchers found that sedum plants grown on 10 cm thickness media are very suitable for use in Michigan, reducing maintenance costs and winter frostbite (Dietz, 2007). Comparing with relevant researches in the United States, the rate of rainwater retention recorded in an earlier study (Monterusso et al., 2004) should be the lowest rate of rainwater retention in all studies, but the reason may be that the number of samples collected in this study is too small (only 4 samples), and only sampled in two consecutive rainfall events. And the Green Roof of different structures will have different water storage capacities. For example, in the study of Vanwoert et al. (2005) and Moran et al. (2004), the water storage capacities of the Green Roofs are $2L/m^2$ and $4L/m^2$ respectively. Table 2-1 shows the average retention of Green Roof, but under different rainfall conditions (rainfall intensity, climate conditions in the year of rainfall) in each experiment the experimental results are quite different. At present, in addition to measuring the amount of Green Roof retention, there are also reports on the reduction of flood peaks and the occurrence time of flood peaks (Vanwoert et al., 2005; Moran et al., 2004; Hutchinson et al., 2003).

Table 2-1: Summary of rainfall retention by Green Roof (Liu, 2009)

Location	Retention rate (%)	Media thickness (cm)	Slope (%)	Rainfall (mm)
Austin (USA)	13-14	10	-	49
	12-88	10	-	12
	100	10	-	<10
Tartu (Estonia)	85.7	10	-	2.1
Augustenborg (Sweden)	63	3	2.6	-
Georgia (USA)	90	7.82	-	<25.4
	<50	7.82	-	>76.2
Michigan (USA)	85.6	6	2	mean
	82.2	6	7	-
	78.5	6	15	-
	75.3	6	25	-
	38.6	2	2	-
	58.1	1	2	-
	69.8	2.5	6.5	-
	70.7	4	6.5	-
	65.9	4	-	-
	68.1	6	-	-
Oregon (USA)	69	12.7	3	-
North Carolina	62	7.6	-	-
	63	10.2	-	-
Europe	85	15	-	-
	65	35	-	-
	75	15	-	-
	81	3	-	-
	27	14	-	-
	45	10	-	-

There is less measured data on water quality of Green Roof. In studies in Oregon, USA, total phosphorus (TP) concentration ranges from 0.2 to 1 mg/L (Hutchinson et al., 2003). In Michigan, in the case of fertilization for the Green Roof test area, the total mean phosphorus concentration of runoff water samples is still in the range of 0.5 to 4 mg/L (Monteruss et al., 2004). One of the test areas has a nitrate ($N0_3$-N) concentration of more than 20 mg/L. , but there is no rainfall background value for this experiment, so the actual rain retention effect should be lower than the experimental result data.

However, in a survey in Wisconsin (Bannerman et al., 1993), two Green Roof runoffs in residential and commercial areas respectively, the total phosphorus concentration is only 0.15 and 0.20 mg/L. A study by Moran et al.(2004) shows that the total phosphorus concentration and output in the Green Roof runoff is much higher than the rainfall Background value, compared to the conventional roof. The difference is not significant. The total nitrogen (TN) concentration in the runoff is also significantly higher than the rainfall concentration. There is no fertilization on the Green Roof, resulting in this result, probably due to the leaching of nutrients in the Green Roof medium.

Hutchinson et al.(2003) in an unpublished study examines the copper concentration in runoff from Green Roof. The test result exceeds the standard value of 9 µg/L three times. The researchers hypothesize that Cu originates from the treated wood or soil medium itself (Dietz, 2007). Therefore, although installing a Green Roof can intercept rainfall, it is important to pay attention to the total nitrogen total phosphorus output. In most case studies, the intercepted rainfall can make up for this, so it is best to choose plants with low fertilization rates. In addition to the Green Roof, the effectiveness of media in the output of pollutants and the study of heavy metals processing and output are still lacking.

2.2.3 Rain Garden/ Bioretention

Rain Garden/ Bioretention is generally built near parking lots or residential areas and is guided through inlets, making rainfall runoff from impervious surfaces enter the retention areas, where a series of biological, physical, and chemical processes of the soil, microorganisms, and plants achieve rainwater retention and water quality treatment. Under actual conditions, water-conducting facilities and underdrains can be laid. Each part of the system, such as pre-treament belts, squats, plants, soils, culverts, overflow outlets, etc., in the grass-groove ditch at the inlet, can remove pollutants and reduce the effect of rainwater runoff. The overall design structure is based on local soil types, environmental conditions and land use patterns.

Another environmental benefit of reducing surface runoff through Rain Garden technology and delaying or reducing rainfall peak is to reduce the load on municipal pipelines and reduce flooding, thereby protecting the water quality of receiving water bodies and reducing river bank erosion. A report from the University of New Hampshire Stormwater Center(UNHSC, 2012) strongly supports this conclusion. The data shows that the average detention time of Rain Garden and the rate of flood reduction exceed 85%. The flood peak time in Rain Garden area lags behind the entrance peak of 615min. In the field experiment of the University of Maryland, the peak retention rate can reach 50-60% (Davis et al., 2006). The reduction in rainfall runoff in Rain Garden varies by season. In April and August in the cold regions, the peak runoff reduction can reach 13% and 26%, respectively, and the total runoff decreases by 13% and 25%, respectively (Muthann et al., 2007). Rain Garden has reduced the effect of heavy rainfall or previous areas with higher water content, but it nonetheless remains one of the means of flood control.

Early Rain Garden studies were mainly performed in laboratories (Davis et al., 2001). Experiments have found that Rain Garden significantly reduces the concentrations of copper, lead, and zinc (>90%). The retention rate of copper, lead, and zinc in the snow melting water can reach 89%, 99%, and 96%, respectively. However, it should be noted that the adsorption capacity of heavy metals by Rain Garden media is limited. After 15-20 years of use, the accumulated heavy metals may reach the level that threatens people's health. Therefore, the amount of heavy metals accumulated in the soil can be reduced by selecting the plant species to be planted and the soil can be periodically repaired. Studies have shown that high organic matter content in soil has a high correlation with metal retention ($P<0.01$). The absorption of heavy metals by plants generally accounts for 0.5-3.3% of the total metal retention. However, due to the different plant species, the amount of heavy metals absorbed by plants in a Norwegian study may account for 2-8% of the total retained heavy metals in the detention zone. The impact of heavy metal accumulation in plants and soil on ecology and its solutions still require further study (Dietz, 2007).

Rain Garden design standards are not yet consistent. In spite of this, studies on Rain Garden can better understand the mechanism of contaminant retention. In addition to phosphorus output and low total nitrogen retention problems, retention zones are very effective at reducing rainwater runoff and many pollutant concentrations. However, long-term field experiments are still needed to obtain data to test how these systems will perform over time and in different seasons. Using different media or different design methods to reduce specific pollutants is an area that needs further study. At present, there have been many meticulous studies on the retention efficiency of metals and nutrients in Rain Garden systems, but it is still a studyable direction in the treatment of bacteria and reduction of water temperature (Dietz, 2007).

The replenishment and protection of the basin's base flow and groundwater is an important goal for the use of Rain Garden technology. However, as of now, there are few studies on related mechanisms, and few people consider this function in applications. In the future research and application, it is necessary to gradually determine the corresponding design criteria, such as designing the annual runoff volume to maintain the hydrological status before development., how to design the biological retention system to achieve optimal groundwater recharge, and use natural subsoil to meet the groundwater when recharging should pay attention to what issues and so on. In particular, attention should be paid to areas where groundwater recharge is a problem (Davis et al., 2006).

2.2.4 Permeable Pavement

Permeable Pavement is designed to control surface runoff, increasing rainwater infiltration into the subsoil (USEPA, 1999). Permeable Pavement includes block brick pavement, plastic grid pavement, porous asphalt pavement, and porous concrete pavement (Dietz, 2007). Many studies have shown that Permeable Pavement is effective to reduce runoff and associated contaminants in a variety of locations (Collins et al., 2008; Pezzaniti et al., 2009; Collins et al., 2010; Fassman & Blackbourn 2010; Tota-Maharaj & Scholz 2010; Beecham et al., 2012). Reduction on average runoff from Permeable Pavement varies from 50 % to 93 % according to Table 2-2. Hunt et al. (2002) presents that 75 % of rainfall events are captured by the Permeable Pavement, and 25 % runs away by runoff from the study site. Collins et al.(2008) found that both continuous permeable concrete pavement and concrete grid paver are able to control runoff effectively. Further experiments have confirmed that not only can Permeable Pavement reduce runoff, but it can also eliminate runoff generation (Bean et al., 2007). Fassman and Blackbourn (2010) used Permeable Pavement to achieve pre-development hydrology. The results are consistent with findings reported by Dreelin et al.(2006) who used Permeable Pavement to reduce 93% of runoff at the site. Research on contaminants removal by Permeable Pavement has been made in many studies. Generally, the average reduction is from 0 % to 94 % shown in Table 2-2. Bean et al.(2007) evaluated the effectiveness of Permeable Pavement on controlling water quality. However, different results have been shown at two study areas. Concentration of NH_3-N was observed to be high at the first study area but low at the second study area. Some studies have also found increased NO_3-N concentrations in water from Permeable Pavement (James & Shahin, 1998; Collins et al., 2010). Permeable Pavement is also effective to reduce metal in water, generally the reduction between 20% and 99% (Table 2-2). Fach et al.(2005) used four types of permeable concrete pavements to remove Cd, Cu, Pb, and Zn based on designed rainfall-runoff events, and received significant results. Meyers et al.(2011) also reported 94 % to 99 % reduction of Z, Cu, and Pb in water stored in Permeable Pavement after several hours. Other studies shown 80% removal of Zn (Dreelin et al., 2006). Pagotto et al.(2000) also demonstrated water quality benefits of Permeable Pavement for Cu and Pb. Dierkes et al.(2002) conducted a test to check the capacity of Permeable Pavement on capturing heavy metals from runoff. The results show that metals can be quickly collected in the top of the Permeable Pavement, leading to a higher pollution risk. Therefore, related maintenance and suitable location selection of the system are key to achieve high performance (Bean et al., 2007; Kwiatkowski et al., 2007). In addition, Permeable Pavement has been shown to be effective to for controlling grease (Newman et al., 2002) and bacteria (Tota-Maharaj et al., 2010). Although Permeable Pavement is often used to control runoff and improve water quality, it can also be applied to store rainwater for reusing as water resources (Meyers et al., 2011).

Table 2-2: Summary of runoff and pollutant retention by Permeable Pavement (Ahiablame et al., 2012)

Location	Runoff	TSS	P/TP	NO3-N	NH4-N	TKN	Cu	Pb	Zn
Rezé (France)	-	58	-	-	-	-	-	84	73
Nantes (France)	-	87	-	-	-	-	20	74	-
Florida (USA)	50	>75	>75	-	>75	>75	>75	>75	>75
North Carolina	75	-	-	-	-	-	-	-	-
Lab experiment	-	-	-	-	-	-	>85	>85	>85
Georgia (USA)	93	-	10	-	-	-	-	-	80
Lab experiment	-	94	-	-	-	-	-	-	-
Edinburgh (Scotland)	-	-	78	-	85	-	-	-	-
Adelaide (Australia	-	-	-	-	-	94-99	94-99	94-99	-

2.3 Evaluation of LIDs based on modeling

With the development of LIDs, the understanding of the effectiveness of LIDs in developed countries is no longer limited to the actual sampling and monitoring, and the rainfall-runoff models that can simulate the LIDs have been gradually developed and promoted. Great progress has been made so far. For example, Villarreal et al.(2004) performed an artificial simulation of the effectiveness of LIDs at different return periods and found that Green Roof can significantly reduce roof runoff. Huber (2004) used SWMM to model LIDs pollution control capabilities for urban runoff. Hayes et al. (2008) used the IDEAL model to simulate the effectiveness of LIDs after site development. The WWHM3 Pro model developed by Lancaster (2008). can determine the scale of LIDs before the design without using complex calculations and continuous simulation, reducing the obstacles to the implementation of LIDs (Drew, 2008).

With the continuous expansion of the simulation scope of LIDs effectiveness, the model has begun to bias the internal processing of simulation research LIDs. For example, Alfredo et al. (2010) used SWMM to simulate the hydrological characteristics of Green Roof of different thicknesses under different rainfall intensities. It is concluded that the runoff coefficient of Green Roof ranged from 0.2-0.7. However, some assumptions were made in the simulation of the Green Roofeffect, and there was a lack of using measured data to calibrate the model (Alfredo et al., 2010). Janet et al. (2008) used SWMM to simulate the suitability of Ballna Creek Watershed and measured rainfall data to calibrate the model. Sensitivity analysis of model parameters shows that the most sensitive parameters are imperviousness in the catchment area and depression detention in the impervious area. The least sensitive parameter is the Manning coefficient (Janet et al., 2008). Brown et al.(2013) used the DRAINMOD model to simulate the hydrological movement of the LIDs. Brath et al.(2006) of Italy evaluated the impact of land use change on urban flooding frequency through hydrological modeling. Boughton (2003) of Australia summarized the method of using hydrological model based on long-term simulation results to evaluate design flood. Lee (2005) simulated the rainfall runoff on the surface of roads, and Ostroff (2005) analyzed the effect of roof greening in New York City by using SWMM.

While studying and deepening the understanding of LIDs, the evaluation of the effectiveness of LIDs has also been emphasized, but the management philosophy and technical system are still not deep enough. For example, Zhen et al. (2001) used AGNPS to simulate the LIDs at the level of the three areas of the site, the subcatchment, and the catchment area, evaluated the effectiveness of LIDs, and proposed an optimization plan with the lowest cost reduction per unit of pollution load (Zhen et al., 2001; Zhen et al., 2006; Zhen et al., 2010). When selecting and designing LIDs, engineering designers are faced with the problem of how to select the optimal measures from a large number of LIDs. Therefore, Pomeroy et al. (2008) used the AHP method to select the LIDs and established a basic decision-support system based on the simulation results to provide a cost comparison of the design of LIDs.

It can be seen that there are many simulation studies on LIDs in developed countries, and most of them are based on actual cases, leading to widely application on practice. Compared with the developed countries, simulation of LIDs in China has a late focus and the research scope is not wide enough. At the end of the 20th century, the problem of urban flooding caused by urbanization in China has caused serious damage to the urban environment, hydrology and ecology (Dong et al., 2007), just as developed countries have faced in the past. Fortunately, with the development of global integration, the sharing of cutting-edge international information has continued to increase. Therefore, China can easily learn from the advanced experience of developed countries to solve the above problems. According to the problem of urban storm in China, many experts and scholars has begun to explore sustainable urban development, including the promotion and simulation of LIDs in China (Hu, 2012).

In recent years, there have been many cases in which Chinese scholars have carried out simulation research on LIDs. Hou (2007) used SWMM to simulate and analyze the peak change of drainage pipes arranged with low elevation greenbelt and detention pond in the Olympic Park in Beijing. The results show that low elevation greenbelt and detention pond can effectively reduce the peak and delay the peak time and increase the use of rainwater resources. Jin et al.(2010) used SWMM to simulate the influence of peak, runoff coefficient, and lag time of porous brick and low elevation greenbelt with different return periods. The results show that both the porous brick and low elevation greenbelt can reduce the peak and runoff coefficient, but the low elevation greenbelt has good rainwater management effect in areas with high rainfall intensity, and porous brick has better rainwater management effect in areas with lower intensity of rainfall. Li et al.(2011) used SWMM to simulate the process of regional outlet flow before and after the development of a community in Tianjin, and evaluated the impact of low elevation greenbelt and reservoir on the runoff in the community. The final results show that both low elevation greenbelt and reservoir can simultaneously reduce peak, delay peak time, and improve rainwater utilization. Zhao et al.(2011) used SWMM combined with Huff method to simulate the independent drainage system, and calibrate the model with measured data. The results show that SWMM can better reflect the service performance of the stormwater drainage system in the study area, which can provide decision support for flood controlling and updating and maintenance of the drainage system. Sun et al.(2011) used SWMM and RECARGA software to simulate the eco-hydrological effects of LIDs and urbanization in the area, analyzed the sensitivity of the design elements of the Bioretention to runoff regulation performance, and explored the different eco-hydrological effects of BMPs and LIDs.

Fu (2012) used PC-SWMM software to simulate the designed rainfall-flooding process of the study area and verified that in the absence of measured data, the comprehensive runoff coefficient as an objective function is feasible for the calibration and verification of model parameters. The results show that in the return period T = 1a, 2a, there will not be a large area of inundating in the study area, but at T = 5a, 10a, many nodes have accumulated water or overflow, pipe load is high, and the full flow time is relatively long. Wang et al.(2012) used SWMM to simulate the hydrological effect of LIDs. The results show that after the urbanization, the peak in the river basin increased significantly, the peak time advanced, and the runoff coefficient increased. Both porous brick and low elevation greenbelt can be effective to relive the stormwater discharge pressure, reducing the peak and runoff coefficient. Wang et al.(2012) used SWMM to simulate LIDs. Results based on rainfall events and continuous weather records show that LIDs at the site can promote the peak and annual runoff to return to the state of pre -development, and the effect of LIDs on the reduction of pollutants is significantly. Wang et al.(2008) used Mike-21 to simulate the flow field of landscape storage water body in seven different design schemes of Jincang Lake of China to optimize the design schemes, and predict and analyze the water quality of Jincang Lake during water transferring to provide a scientific basis for the design and management of Jincang Lake. Zhang (2005) used MUSIC to research the effect of combined practices of vegetation trench, rainwater detention zone and detention pond to select the optimal scheme. Chu (2010) used DSS to simulate the reduction of average annual runoff, and carried out a cost-benefit assessment. Chou (2004) established an optimization model to design the LIDs. Taking the Feicui Reservoir of China as the case, a dynamic design optimization model was used to determine the solution.

At the same time, the minimum cost was used as the optimal objective function and the standard pollutant concentration as constraint condition. The whole study area was simulated and optimized. Yang (2008) performed parameter sensitivity analysis on TOOLBOX, and simulated the effectiveness of rainwater management measures using a designed storm by the exchange module method to study the impact of non-point source pollution and water quality change. Zhong (2006) used AGNPS to simulate the differences in the design of rainwater management measures before and after, and analyzed the effectiveness of rainwater management measures. Tan et al.(2007) used Info-Works CS to evaluate the effect of rainwater optimization management in residential areas. The results show that the use of Permeable Pavement, green space and landscape water can achieve good runoff peak reduction effect, and can control the runoff coefficient of this ecological community at a relatively low level. Kang (2012) used Mike-21 to simulate the changes of COD, ammonia nitrogen, TN and TP in landscape water based on the data from May to June of 2011. Through the error analysis of simulated and measured values, the feasibility and effectiveness of Mike-21 were verified. Based on the results of simulation analysis, schemes of improving and maintaining the quality of landscape water ware proposed. Tang (2010) used SUSTAIN to conduct comprehensive planning and management of BMPs in the study area and gave the optimum rainfall-runoff management design. Niu et al.(2012) used SWMM and WASP to simulate the use of rainwater on landscape rivers. The results show that the comprehensive application of SWMM and WASP models can effectively solve the problem of water quality simulation of rainfall runoff discharge into landscape waters. Dong et al.(2008) combined SWMM with the water quality model developed by the Department of Environment of Tsinghua University, taking the Hewan District of Shenzhen of China as study area to evaluate the proposed drainage system planning and its effect on water environment in Hewan District using the integrated tool.

The above-mentioned large number of case studies show that although there have been simulation studies on LIDs, most of them lack model calibration and verification and directly use experience parameters, leading to the accuracy of the final simulation to be further verified. Many simulations are abstractions of research objects. The scenario of the situation has been separated from the actual planning of land use in the study area. Therefore, the simulation results of the rainfall-runoff model can only stay at a purely academic level in China, and it is not sufficient to guide the design and construction of LIDs. Even if the construction is completed, the reconstruction and re-engineering must be carried out in the later period, wasting a lot of financial resources and intensifying the contradiction between urban planning and urban ecosystem, which is one of the important reasons for the slowness of LIDs in China.

In summary, in terms of urban storm management in China, LIDs based on decentralized idea are mainly based on advanced concepts and experiences from developed counties. Application and practices are still in their infancy in China. In addition, simulation studies on LIDs are mostly limited to single measure evaluation, which is not representative, and there is a lack of more practical simulation studies on large spatial scale and combined LIDs.

3. Introduction of the study area

3.1 Overview of runoff risks in China

Precipitation in China is affected by the southeast monsoon and the southwest monsoon, and is unevenly distributed in different seasons of the year. It’s interact variation is large. The precipitation is mainly concentrated from June to September, accounting for 60% to 80% of the whole year. The north even accounts for more than 90%. Meanwhile, the uncertainty of climate change in China has brought about frequent risks such as heavy storms and increased flood peak, which has led to frequent occurrence of flooding in summer each year. At the same time, due to the large runoff peaks during the wet season, most of runoff have not been utilized or infiltrated, resulting in the alternating occurrence of river cutoff and flooding, and the risk is getting higher and higher. The data shows that the ratio of the maximum peak discharge to the average annual maximum peak discharge is 5 to 10 times in the north, 2 to 5 times in the south, and uneven within the year and between the years and between regions, resulting in excessive risk of flooding (Gong, 1998). In addition to the regional floods, the problems in urban areas have become increasingly serious. In 2010, surveys of 351 cities (mostly large and medium-sized cities) in 32 provinces (autonomous regions and independent municipalities) in China found that the urban flooding in China is intensifying. During the period 2008-2010, 213 of the cities surveyed had experienced internal waterlogging in varying degrees, of which 137 cities had experienced more than three times. Cities with a floodwater depth of more than 0.5m account for 74.6%. Flooding depth exceeds 0.15m for more than 90%, and flooding retention time exceeds 30min for 79% (Hou et al., 2012). In July 2012, 79 people were killed and economic losses amounted to nearly 10 billion yuan by a heavy storm in Beijing. This is a typical manifestation of urban flooding in China.

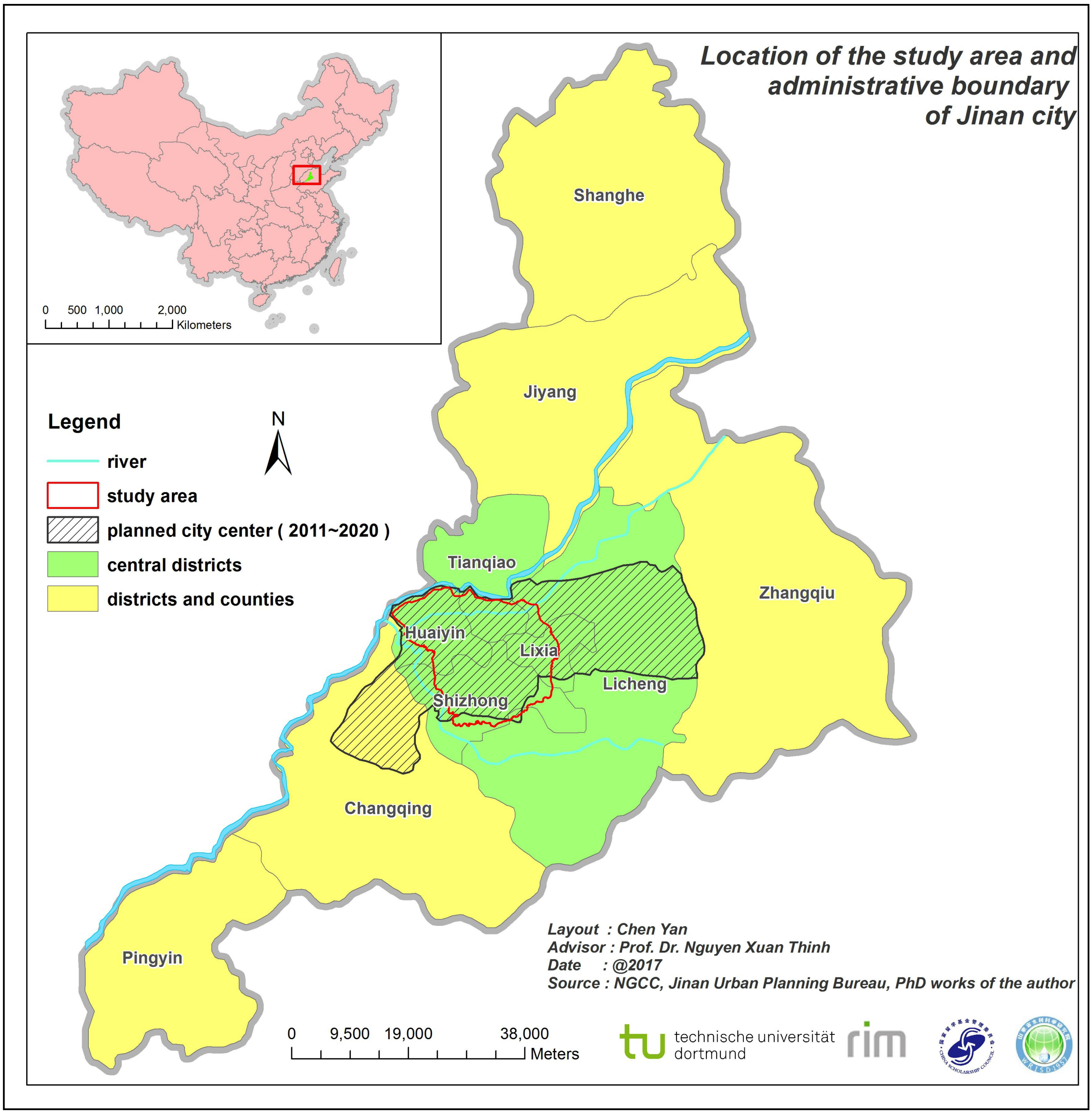
The development of water resources in China is unprecedentedly excessive, especially in the northern regions, where the lower reaches of the Yellow River, the Tarim River, and the Heihe River etc. have ceased to flow, and wetlands and lakes have disappeared in large areas (Wang, 2010). The problem of serious over-exploitation of groundwater has also been aggravated. The area of groundwater over-exploitation in China has reached

190,000km^2, and many groundwater funnels in the north have faced a serious crisis of depletion of groundwater resources. At the same time, China's surface water quality is not optimistic. In 2012, according to the monitoring data of the National Water Resources Quality Monitoring Station of China, the “Environment quality standards for surface water(GB3838-2002)” was used to evaluate the water quality of 201,000 km rivers in China. The results show that the Class-I rivers accounted for 5.5% of the assessment river length, Class-II rivers accounted for 39.7%, Class-III rivers accounted for 21.8%, Class-IV rivers accounted for 11.8%, and Class-V rivers accounted for 5.5%. Inferior grade rivers accounted for 15.7%. Of the 27,000 km^2 water surface of the 103 major lakes in China, there were 32 lakes with the total annual water quality of Class-I to Class-III, accounting for 28.6% of the total number of assessed lakes, 44.2% of the assessed water area. There were 55 Class-IV and Class-V lakes, accounted for 49.1% of the total number of assessed lakes and 31.5% of the assessed water surface area. 25 lakes with inferior V water quality accounted for 22.3% of the total assessed lakes and 24.3% of the assessed water surface area (China Water Resource Report, 2013). Coastal areas in China also exhibit severe eutrophication. For example, in 2003, a total of 119 red tides were discovered over the entire sea area of China, with a cumulative area of approximately 14,550 km^2 (Tang et al., 2005). In addition, about 50% of urban areas have serious groundwater pollution. In 2011, Beijing, Liaoning, Jilin, Heilongjiang, Shanghai, Jiangsu, Hainan, Ningxia and Guangdong(autonomous regions, municipalities) had made sampling analysis based on “Groundwater quality standards (GB/T14848-93)” of China. The results show that Class-I and Class II monitoring wells with water quality suitable for various purposes accounted for 2.0% of the total number of evaluation monitoring wells. Class-III wells suitable for drinking water sources and industrial or agricultural water accounted for 21.2%, and other classes were 76.8% (China Water Resource Report, 2012).

Urbanization and various gray infrastructure construction lead to vegetation destruction, soil erosion, impervious surface increase, fragmentation of rivers and lakes, disruption of surface water and groundwater connectivity, and drastically changed the hydrological conditions such as runoff confluence. In recent 50 years, the runoff of many rivers has changed drastically, and the construction of dams led to a large decline in the flow of most of the rivers, and the decline rate of rivers in China exceeded 30% (Milliman et al., 2000). Since the 1990s, large-scale floods and unfavorable combination of floods have occurred in the Yangtze River, the Songhua River, the Liaohe River, the Pearl River, the Huaihe River, and the Taihu Lake Basin, etc. The design flood volume has been greatly increased (Wang, 2010). Over-reclamation of wetlands and floodplains have led to a 15% reduction in the lake area and a 28% decrease in the area of wetlands, which has reduced the capacity of the river for flood discharge and flood storage. The case of cutting bends to straights along the lower reaches of the Yangtze River shows that the length of the original river channel has been shortened by 1/3 since it was straightened, and the river gradient has increased. This has led to an increase in river erosion and other negative effects (Pan, 2001). Raising the embankment standards in local areas has increased the risk of flooding in adjacent areas. These projects have almost completely changed the ecological environment of rivers. By the end of 2011, 290,000 kilometers of embankments have been built in China, seven times the number since the found of the People’s Republic of China. At the same time, the number of reservoirs increased from 1,200 to 87,200, and the total storage capacity increased from approximately 20 billion cubic meters to 706.4 billion cubic meters (Zhou, 2011). After construction of the Three Gorges Reservoir of China, biodiversity has been drastically reduced and pollution has intensified. Eutrophication of water bodies has occurred in reservoir backwater areas (Huang et al., 2012; Zeng et al., 2006), fish reduction (Yi et al.,, 2010), and fish habitat decline (Wang et al., 2009; Li et al.,2012; Yi et al., 2013).

3.2 Study area

The study area is located in Jinan which is in the west middle of Shandong province of China. Jinan is geographically located between longitudes 116°11´E and 117°44´E, latitudes 36°02´N and 37°31´N, and is a political, economic, cultural, scientific and technological education and financial center of Shandong province. It is a transport hub connecting North China and East China, coast and inland. The city has a total area of 8,177km^2 and an central urban area of 2,157km^2 (Figure 3-1).



Layout : Chen Yan
Advisor : Prof. Dr. Nguyen Xuan Thinh
Date : @2017
Source : NGCC, Jinan Urban Planning Bureau, PhD works of the author

Figure 3-1: Location of the study area and administrative boundary of Jinan city

The study watershed is located in the mid-latitudes of North China and belongs to the warm-temperate and semi-humid continental monsoon climate zone. The average annual precipitation is 617.2mm. The general distribution trend is greater in the south than in the north, and is greater in the middle than in the east and west. The average annual precipitation in the middle and low mountainous areas in the south is between 700 and 750mm. The average annual precipitation in the central hilly areas is between 600 and 700mm. The annual average precipitation in the northern plains is between 550 and 600mm. The distribution of precipitation in the year is very uneven, mainly concentrates in wet season from June to September, which accounts for about 75.5% of the whole year, forming a summer flooding period. The largest annual precipitation in history was 1145mm, which occurred in 1962, and the minimum precipitation was only 336mm. The precipitation in Jinan varies greatly from year to year, with complex topography and geomorphology. In addition, large urban population and poor drainage facilities lead to frequent and severe flooding. Xiaoqing River is the only flood discharge channel in Jinan and the coastal areas. The drainage area of the upper reaches of the Huangtaiqiao hydrological station in the urban area is 397.4 km^2. There are 11 tributaries in the Huangtaiqiao watershed. Most of them are flood-producing river channels and are unilaterally comb-toothed on the left and right banks of the river. The main tributaries are Quanfu River, Liuxing River, East Luo River, West Luo River, East Gongshang River, West Gongshang River, Xingji River, Lashan River, South Taiping River, North Taiping River and Hongxi Channel (Figure 3-2). The branches on the right bank have steep rushes, and the upper reaches of the cross-section are larger than the downstream. When heavy rainfalls, the discharge is not enough, which often causes downstream flooding of tributaries. In addition, A micro site in a subcatchment with a high runoff coefficient value was selected as the sub study area (Figure 3-3). It was used to build 3D scene and simulate the effect of LIDs on regulating runoff from extreme storms.

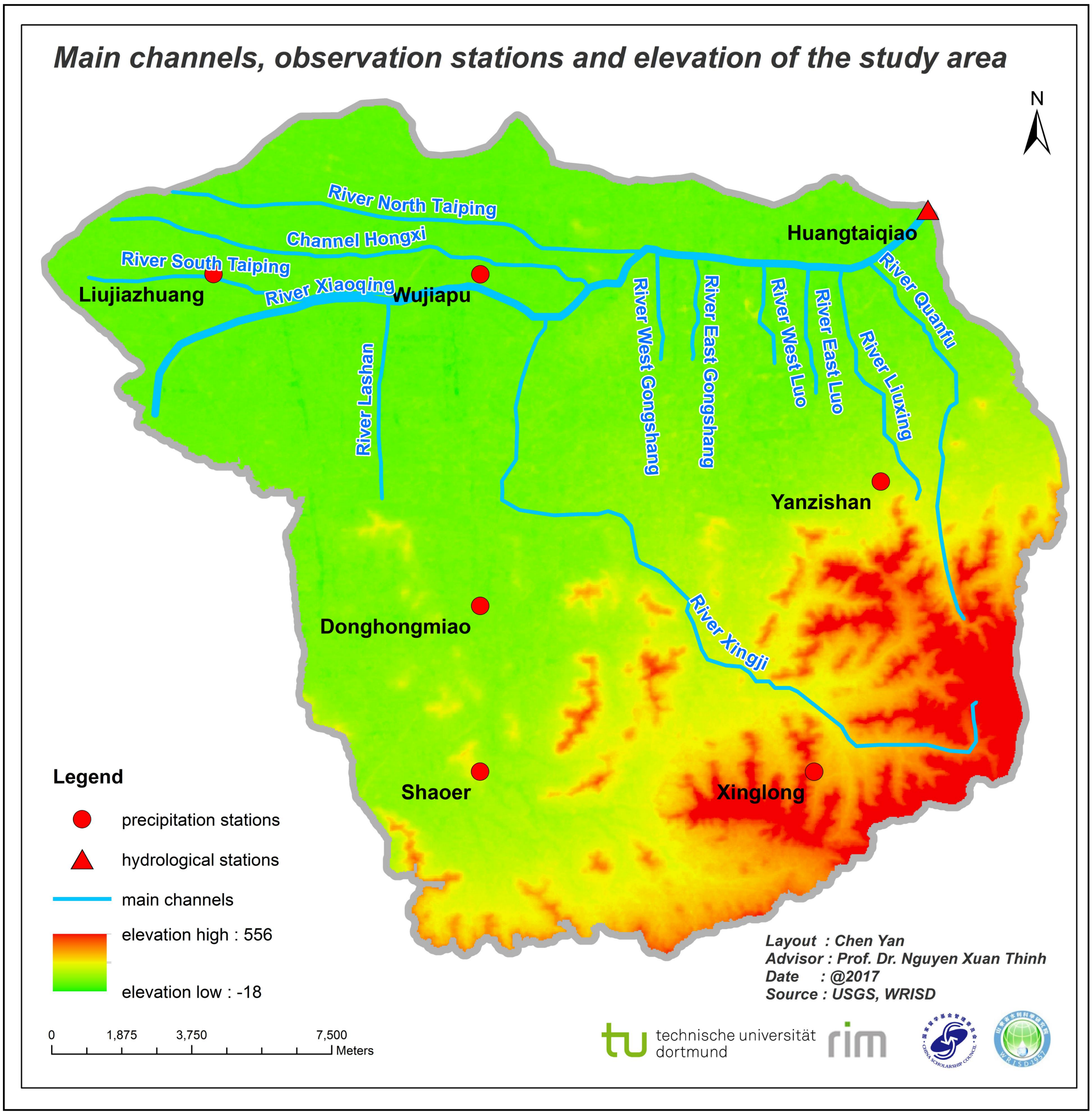


Figure 3-2: Main channels, observation stations and elevation of the study area

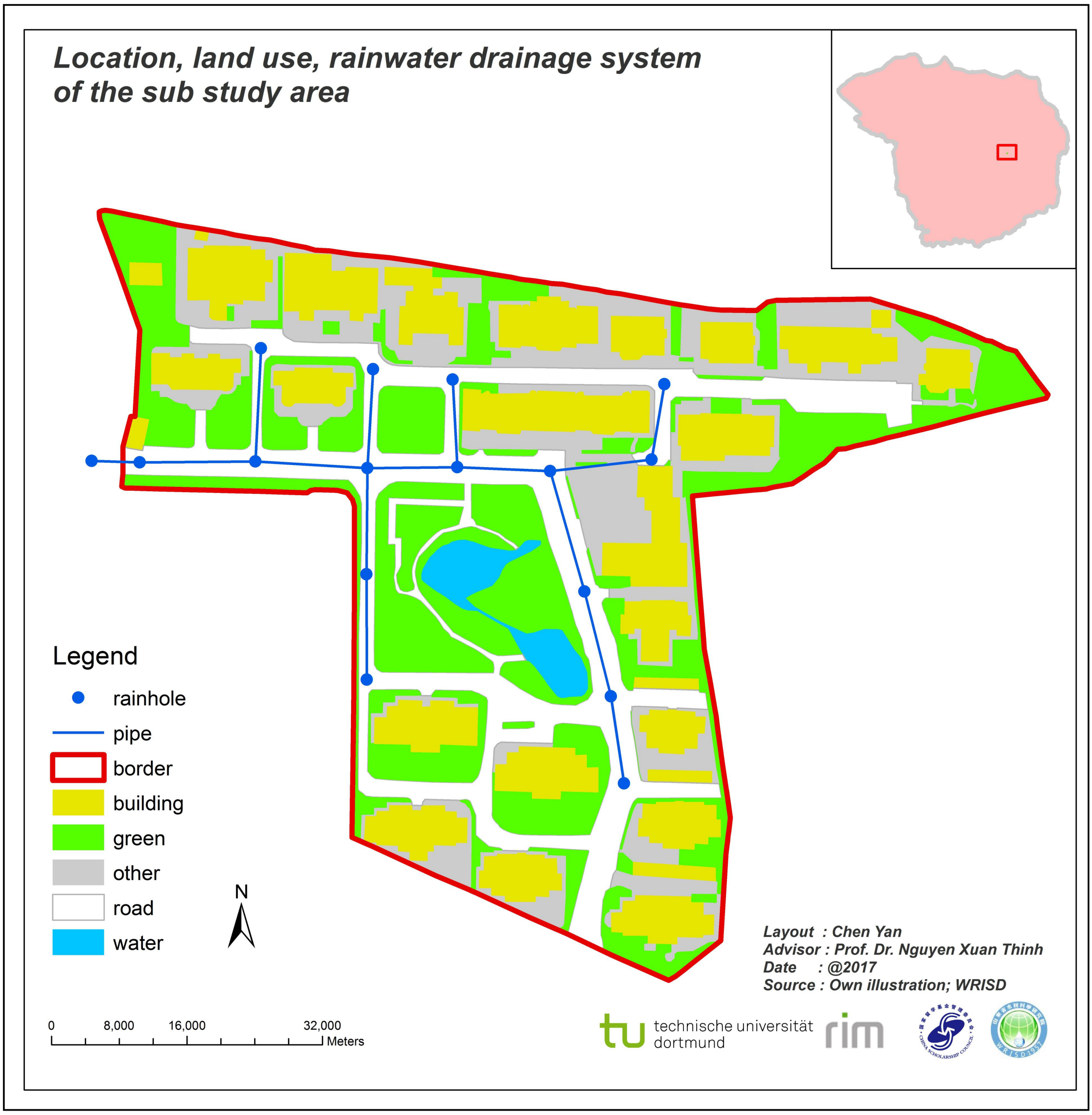


Figure 3-3: Location, land use, rainwater drainage system of the sub study area

In the study area, major problems related to urban flooding and rainwater use are summarized as follows:

1) Incomplete urban rainwater drainage system

Incomplete urban rainwater drainage system, low design standards, and unmatched ability of flooding discharge of upstream and downstream reaches lead to problems such as flooding on the roads, urban waterlogging and river overflow. The Xiaoqing River and other mainstreams have narrow cross-sections and low flooding control capabilities. Due to backwater effect, tributary floods can not be discharged in time. Tributaries of the Xiaoqing River have narrow cross-sections in the middle and lower reaches, and the river is heavily silted. The current status of the flooding discharge capacity is only for floods with 10-year and 20-year recurrence intervals, which is far from the 100-year standard of planned flooding control. The flooding level of the river also affects the drainage of storm pipes, resulting in frequent urban flooding disasters. In addition, the rivers are invaded by sheds and the phenomenon is serious, affecting the normal functioning of the flood discharge. According to the statistics, the area covered by sheds is about 150,000 m^2, and 180,000 m^2 of the river area is occupied. Flooding discharge is affected, on the other hand, it also increases the difficulty of cleaning watercourses and increases economic losses. The rivers in the city such as the Xingji River and the East Luo River are both covered by sheds, and most of them are used as commercial land.

2) Flood detention areas or low-lying areas have been developed and utilized, which weakens the capacity of urban flooding control

Due to the special geographical conditions of Jinan city, historically the formation of depression areas and lakes along the banks of the Xiaoqing River can regulate and store rainwater. However, as the development of the city, these areas have been gradually occupied resulting in reduction in the capacity for regulation and storage. Once the flood comes, it will cause greater economic losses.

3) Flood prevention and drainage projects are not complete

There is a lack of regulating buildings in the outlet of the Xiaoqing River. In the event of a major flood, the flood will fall into a disaster. Floods in the mountainous areas in the upper reaches of urban areas are concentrated within a short time to pound urban areas, causing the rapid formation of street flooding resembling flash flooding in the southern part of the city. The northern part of the urban area is flat and the existing urban rivers, drainage network and water conservancy facilities are in disrepair, and waterlogging is severe. The capacity of flooding discharge has been severely declined.

4) Insufficient projects and capital investment, low urban greening rate

One of the difficulties in the use of rainwater in Jinan city is a serious lack of capital investment and a low rate of urban greening, and it is impossible to obtain advanced technologies and equipment, which makes it extremely difficult to use rainwater. The urban greening rate is low and the natural water storage capacity is poor. According to the statistical yearbook of Jinan, the greening rate in Jinan City in 2016 reached 40%. However, in fact, the southern mountainous area has a large area and dense vegetation, which has greatly improved the overall rate of greening in Jinan. The greening rate in urban areas is obviously low, green areas are scarce, hardened roads extend in all directions, and impervious surfaces cover most of the urban areas. This results in a rapid increase in the rate of runoff during heavy rainfalls and a significant increase in surface runoff. On the other hand, the southern mountainous area is the main source of flood, and the natural hydrological cycle has important practical significance for regulating the flow of flood However, overuse and development in recent years have reduced the vegetation coverage rate in southern mountainous area. The disturbance of human activities has affected the original natural hydrological cycle, meanwhile the original runoff regulation system has been damaged. The surface flood flow has increased year by year, and soil erosion has become increasingly serious. At the same time, flooding projects in Jinan each year are limited, which does not meet the requirements for sustainable development in Jinan.

5) Unreasonable urban planning

Early urban planning in Jinan lacked scientific measurement and long-term considerations. The construction of urban functional areas was mainly based on the degree of economic development. For example, in the construction of residential quarters, most of the considerations were economic factors. Many low-lying areas were developed into residential areas because of their relatively superior geographical locations. When it rains, the amount of accumulated water in these areas is relatively large, which brings security problem. What’s more, to reduce construction costs, many roads were built strictly along major flood discharge routes. This is understandable from the point of view of project construction. However, from the perspective of flood control, the pervious rates of roads have decreased dramatically, being the main flood discharge routes to create more convenient conditions for the confluence of flood and pose a potential threat to urban security. In addition, the current design standards of the drainage network in Jinan are on the low side, and the design return period is only 2 to 5 years. It is far from being able to withstand the current risk of heavy storms. When a heavy storm occurs, once the storm intensity exceeds the urban draining capacity, it will have an adverse impact on social life and cause heavy losses.

Figure 3-4, 3-5 and 3-6, the field pictures of the study area show the existing major problems in Jinan mentioned above. At the same time, as one of bases for selecting LIDs, these pictures will be displayed and discussed again in the following chapter 4.

Figure 3-4: Rainwater drained directly from roofs to roads (Source: WRISD, China)

Figure 3-5: Lacked vegetation layers (Source: WRISD, China)

Figure 3-6: Corrupted pavement (Source: WRISD, China)

3.3 Data

As shown in Table 3-1, the spatial data and attribute data used in this study include basic GIS data, remote sensing images, DEM (Digital Elevation Model), soil data, land planning maps, meteorological and hydrological data, urban rainwater drainage system data, statistical data and design standards. The basic GIS data mainly includes roads, buildings, and administrative boundary data, which was surveyed and produced by NGCC (National Geomatics Center of China) in 2016. Based on this data, spatial analysis module of ArcGIS was used to determine the length and area of the line features and polygon features in the study area, which were used as SWMM modeling input parameters as well as for mapping. In China, because many cities lack a complete spatial database and data sharing level is low, historical land use data is difficult to obtain. In this study, based on remote sensing images of Landsat with 30m spatial resolution (date: 1979, 1989, 1999, 2009, 2017, see Figure 3-7), land cover maps of the study area were classified and extracted according to the method of interpretation firstly, and then historical land use maps were produced by overlay analysis module of ArcGIS, in terms of land planning maps and the national land use classification standards of China. DEM with a spatial resolution of 30m was used in this study for subcatchment partition and slope extraction. At the beginning of the study, there were two main DEM sources to be selected. One is the Aster GDEM (Global Digital Elevation Map) produced by NASA of USA, with a spatial resolution of 30m. Another one is SRTM (Shuttle Radar Topography Mission) data from DLR (Deutsche Zentrum für Luft- und Raumfahrt), with a spatial resolution of 30m. By comparing the two DEM data sources, it was shown that the latter can better describe the details of the geographic features. However, the SRTM spatial data by DLR is distributed in the shape of cross, only 40% area of China has been covered, so Aster GDEM was eventually selected as elementary DEM. The infiltration process need to be simulated by SWMM to estimate runoff, so soil characteristics parameters in the study area were prepared firstly. This study used HWSD (Harmonized World Soil Database) by FAO (Food and Agriculture Organization) of the United Nations to estimate related soil parameters. HWSD contains global-scale soil spatial data and attribute data, which is applicable to large or medium scale. The meteorological data mainly includes the measured precipitation data of five rainfall observation stations and one hydrological observation station in the study area and the evaporation data in the study area. Locations of rainfall stations and hydrological station are shown in Figure 3-2. Hydrological data mainly includes measured runoff data from hydrological station in the study area and cross section data of main reaches of the Xiaoqing River. Measured runoff data was used for calibration and validation of the model. Cross section data was used as input parameters of SWMM. Urban rainwater drainage system data includes rainwater pipes and rainholes and related parameters such as lengths and cross section shapes of the pipes (Figure 3-3). In addition, national standards and parameters values recommended by SWMM User's Manual were also used in the design and simulation of combined LIDs scenarios, which will be discussed in detail in later chapter.

Table 3-1: Data used in the study

Data	Date	Sources
Basic GIS data (administrative boundary, roads and buildings etc.)	2016	NGCC (National Geomatics Center of China)
Landsat 1-3 MSS Landsat 4-5 TM Landsat 8 OLI	1979,1989,1999 ,2009,2017	USGS (United States Geological Survey)
DEM	2011	NASA (National Aeronautics and Space Administration, USA)
Soil data	2008	FAO (Food and Agriculture Organization, UN)
Urban rainwater drainage system data	2016	WRISD (Water Resources Institute of Shandong, China)
Master planning map	2020	Jinan Planning Bureau
Meteorological and hydrological data	2006-2010	WRISD (Water Resources Institute of Shandong, China)
Statistical data	1984-2016	Year Books

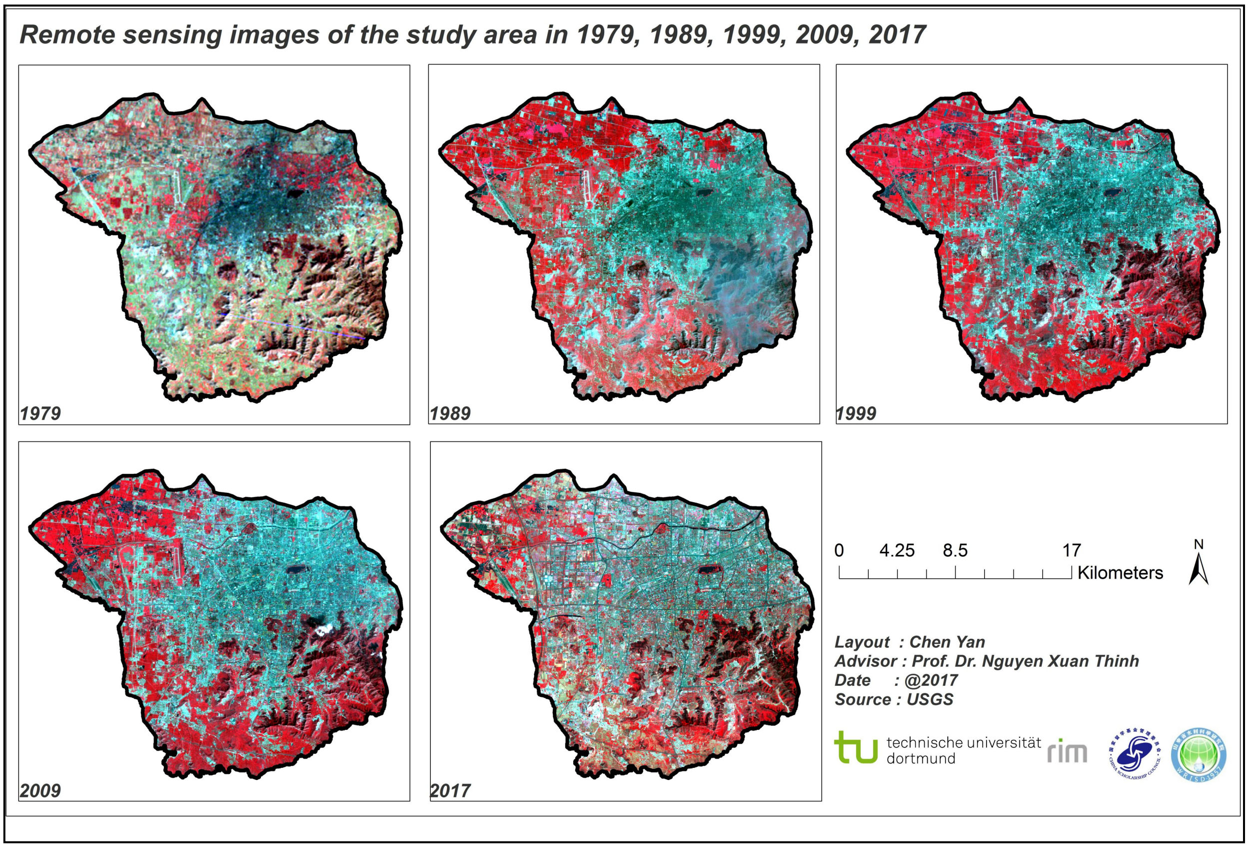


Figure 3-7: Remote Sensing images of the study area in1979,1989,1999,2009,2017

4. Methodology

The methods presented in this chapter contain three sections. Section 4.1 describes the building of SWMM, which includes elements conceptualizing and watershed down-scaling, runoff modeling and parameter estimation based on RS, GIS and underlying surface data. Section 4.2 presents LIDs conceptualizing and scenarios designing of LIDs and extreme storms based on the results of individual LIDs research, design storm formula of the study area and “Chicago” model, used to evaluate the effectiveness of combined LIDs at watershed scale and extreme storms. 4.3 illustrates the methods associated with inundated area estimation and building of 3D scene based on seed algorithm, ArcScene and SketchUp to provide a visualized evaluation method for the planners. Figure 4-1 shows the schematic diagram of workflow.

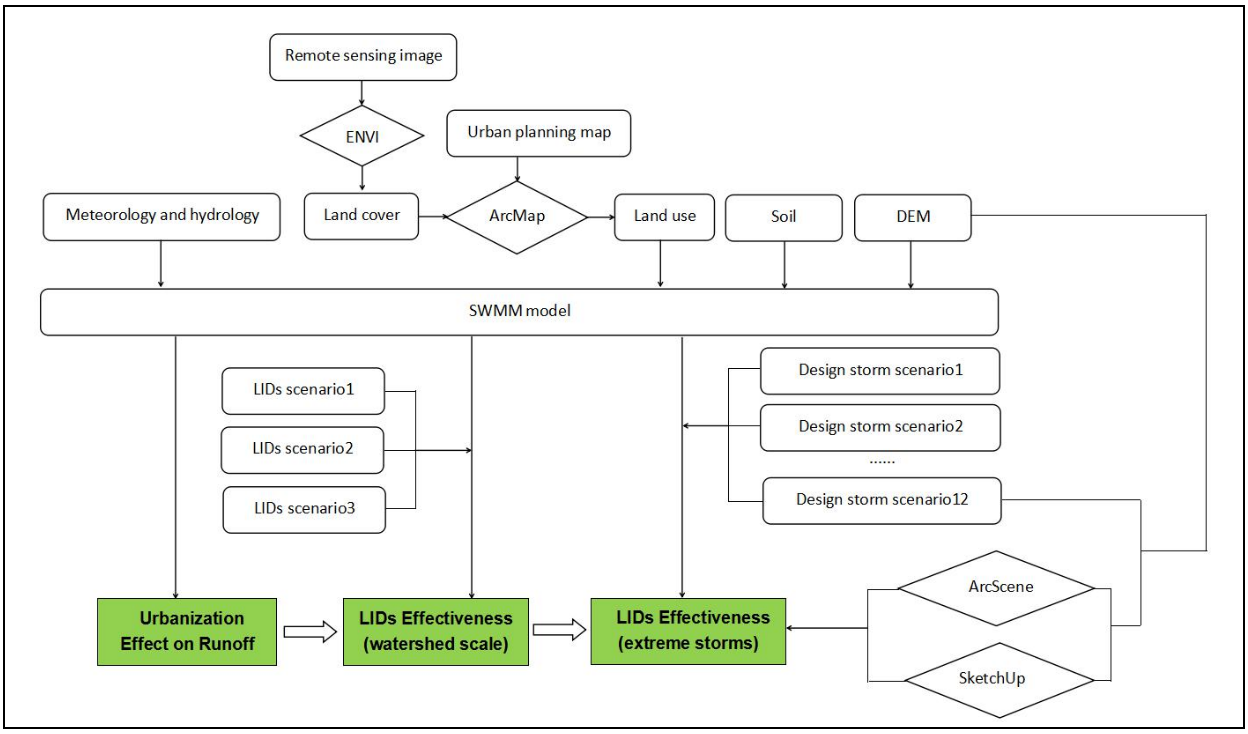


Figure 4-1: The schematic diagram of workflow of the study

4.1 Building of SWMM (Storm Water Management Model)

4.1.1 Elements conceptualizing and watershed down-scaling

LID is a development pattern based on source control, decentralized processing concepts to achieve rainwater control, restoring natural hydrological conditions. It is based on effective modeling in terms of facility combination, simulation analysis, and program evaluation. Selecting a reasonable hydrological model can provide design guarantees for LIDs, transforming the complex relationships of various natural elements, human behaviors, and other influencing factors into a procedural system that can be directly understood, thus facilitating the planning and decision making of LIDs by designers. Reasonable LIDs design needs to simulate different land use scenarios in the planning area, generally including three scenarios before the development of the proposed area, the development of the conventional drainage network and the development of the ecological LID pattern. According to domestic and abroad literature, models related to LIDs mainly include MOUSE, MUSIC, P8-UCM, PURRS, SLAMM, Storm Tac, SWMM, SUSTAIN, L-THIA-LID etc. (Wang et al., 2010). This study selects SWMM for LIDs simulation, because (Wang et al., 2010):

1) SWMM has relatively complete runoff generation and distribution modules that can accurately represent the hydrological cycle of the study area;

2) SWMM can simulate single storm event as well as continuous long-term rainfall-runoff;

3) SWMM can simulate the effect of land use change on the runoff;

4) SWMM is a open source model, easy to be extended in the future research;

5) Independent LIDs modules have been integrated in the model and typical LIDs can be simulated without extra modifications;

SWMM was developed by the US Environmental Protection Agency (EPA) in 1971. It has been continuously improved for decades, and it integrates hydrological, hydraulic and water quality simulation functions (US EPA, 2016). Generally, it can be used for urban drainage network design, rainwater control and pollution reduction facilities design and evaluation.

Figure 4-2 displays how SWMM conceptualizes the elements of the actual drainage system. A Rain Gage module and a Subcatchment module are used to model the rainfall process and runoff process as base. The drainage facilities such as manhole and pipe of the drainage system are simulated with a network consisting of Nodes and Links. Nodes are point elements representing junctions, storage systems, or dividers. Links connect nodes to one another with pipes, channels, pumps, or flow regulators (orifices, weirs, or outlets) (US EPA, 2016).

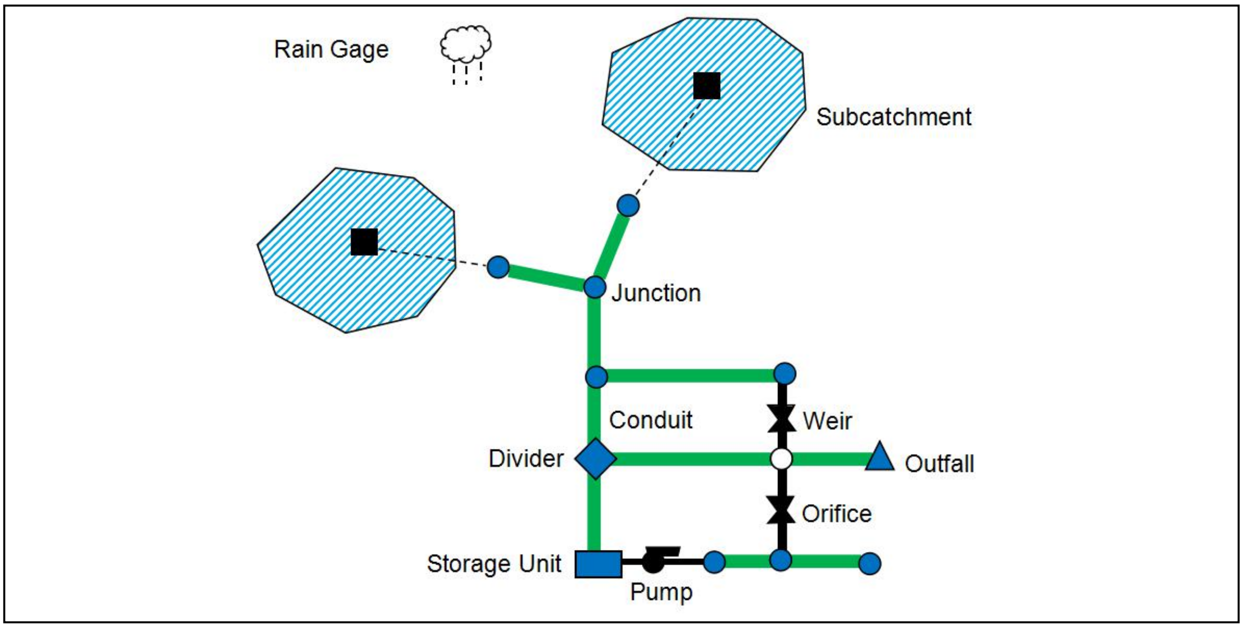
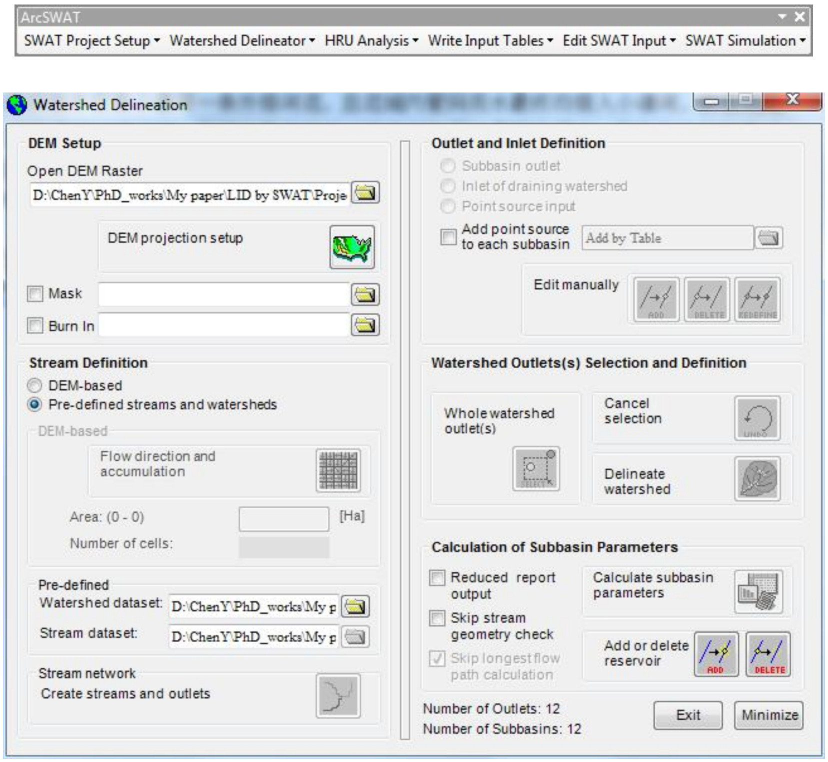


Figure 4-2: SWMM's conceptual model (Source: EPA, USA)

To describe the spatial variability in underlying surface properties and drainage networks, a large study area requires to be discretized into several subcatchments. Generally, a topographic map is often used to identify the drainage boundaries as discretization base, while the location of major raininlets can be determined by using a urban drainage system map. In an urban area, subcatchment discretization based on only topography might not be adequate, for example the pipes might transport rainwater in a direction opposite to the overland gradient. Therefore, subcatchment boundaries must be determined by using both topography and planned drainage system map. In this study, the study scale is extended from the urban site to the larger watershed. The details of the urban drainage system can be simplified. At the same time, since the Xiaoqing River is the only one river to drainage rainwater in Jinan, the distribution of major rivers without consideration in drainage network is selected to determine boundaries of subcatchments and conceptual transportation system. The specific method is to use the watershed functional module (Figure 4-3) of the ArcSWAT plug-in integrated in the ArcGIS's water analysis module, based on DEM and the actual river map of the study area, to partition the study watershed into several subcatchments, namely a process of spatial down-scaling. Subcatchments are displayed in Figure 4-4.



Open DEM Raster: D:\ChenY\PhD_works\My paper\LID by SWAT\Proje

☐ Mask

☐ Burn In

○ DEM-based

● Pre-defined streams and watersheds

Watershed dataset: D:\ChenY\PhD_works\My p

Stream dataset: D:\ChenY\PhD_works\My p

○ Subbasin outlet

○ Inlet of draining watershed

○ Point source input

☐ Add point source to each subbasin

☐ Reduced report output

☐ Skip stream geometry check

☑ Skip longest flow path calculation

Number of Outlets: 12

Number of Subbasins: 12

Figure 4-3: The toolbar and window of ArcSWAT plug-in

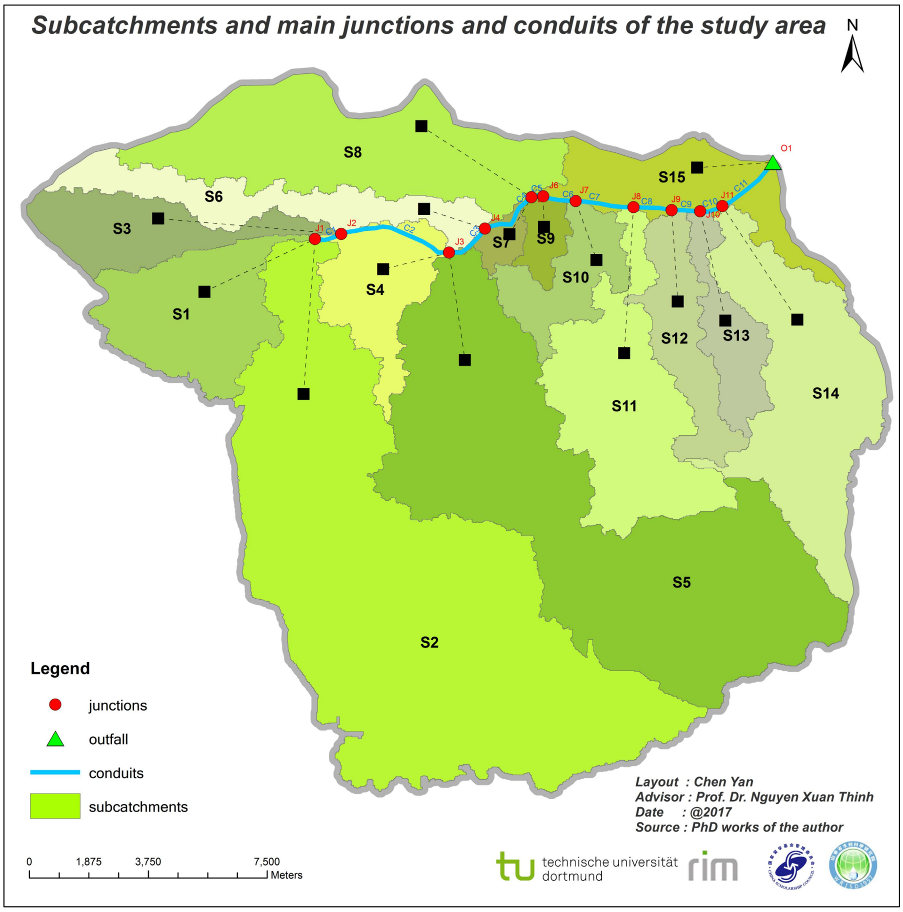


Figure 4-4: Subcatchments and main junctions and conduits of the study area

4.1.2 Runoff modeling and parameter estimation

A subcatchment in SWMM is conceptualized as a rectangle with a uniform slope S and a width W that drains to a single outlet pipe or channel as shown in Figure 4-5. Runoff is generated by modeling the subcatchment as a nonlinear reservoir, as depicted in Figure 4-6 (EPA,USA, 2016).

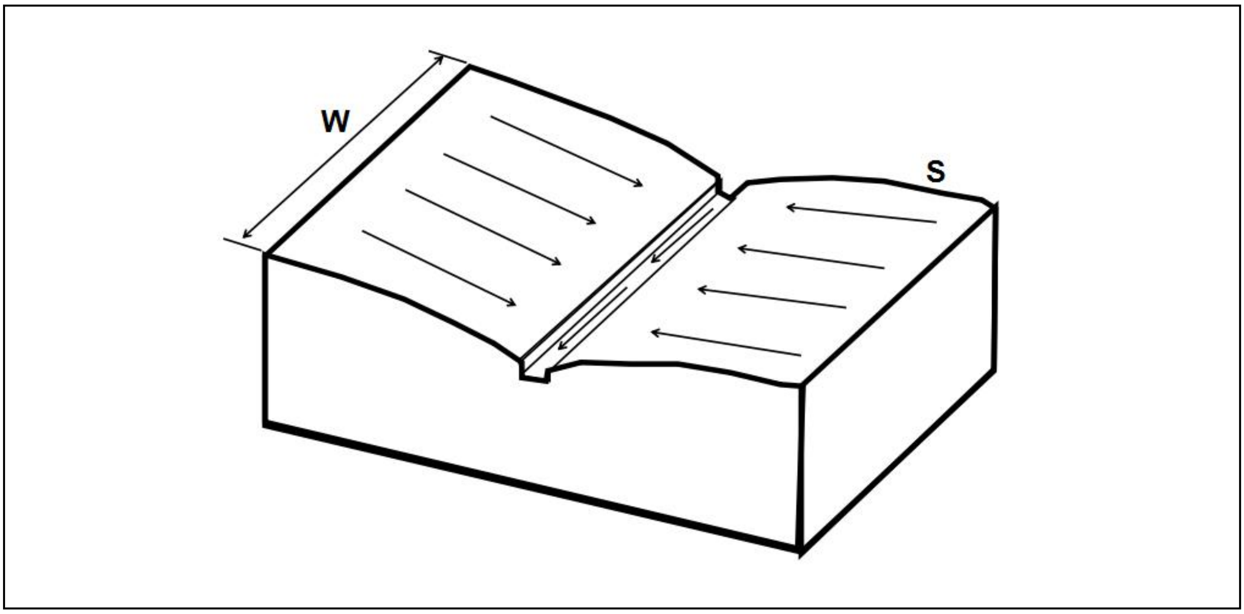


Figure 4-5: Subcatchment representation in SWMM (Source: EPA, USA)

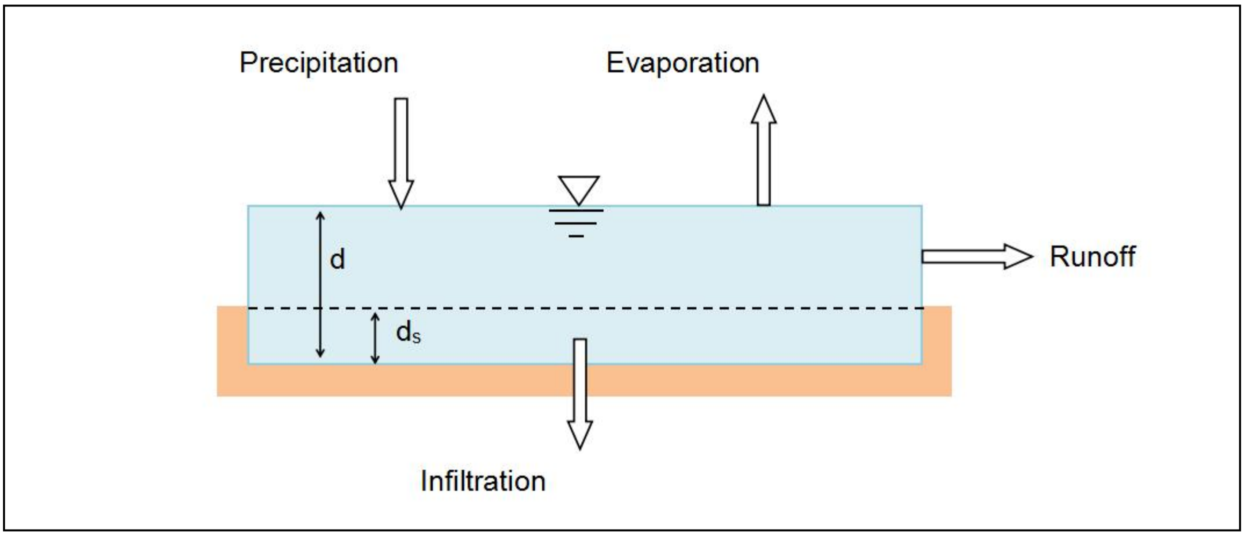


Figure 4-6: Nonlinear reservoir model of a subcatchment (Source: EPA, USA)

The subcatchment acquires inflow from precipitation and losses from evaporation and infiltration. The net rainfall accumulates on the surface of subcatchment to a depth d. Collected rainwater except the depression storage (depth d_s) can be runoff q. Depression storage represents the initial rainfall abstractions such as interception by vegetation and soil wetting. According to conservation of mass, variation in depth d per unit of time t is simply the difference between inflow and outflow changes of the subcatchment, as shown by following equation:

$$\frac{\partial d}{\partial t} = i - e - f - q \tag{1}$$

where i is rate of rainfall, e is evaporation rate, f is infiltration rate, q is runoff rate. Assuming the subcatchment as a wide open rectangular channel with a width W, height d-d_s, and slope S, the Manning equation can be applied to estimate the runoff volume Q as Eq.(2):

$$Q = \frac{K}{n}\sqrt{S}\sqrt[3]{R^2}A_{cs} \tag{2}$$

where K is a conversion factor between International System of Units and English Units, n is a roughness coefficient, S is the average slope of the subcatchment, A_{cs} is the cross section area of the channel, and R is the hydraulic radius associated with this area. Referring to Figure 4-5 and 4-6, A_{cs} is the rectangular area with width W and height d-d_s. Because W will always be much larger than d it follows that $A_{cs}=W(d-d_s)$ and $R=d-d_s$. Substituting these expressions into Eq.(2) gives:

$$Q = \frac{K}{n}W\sqrt{S}\sqrt[5]{(d-d_s)^3} \tag{3}$$

to determine the runoff rate q, Eq.(3) is divided by the area of the subcatchment A_s:

$$q = \frac{K}{nA_s}W\sqrt{S}\sqrt[5]{(d-d_s)^3} \tag{4}$$

substituting Eq.(4) into Eq.(1) results in:

$$\frac{\partial d}{\partial t} = i - e - f - \frac{K}{nA_s}W\sqrt{S}\sqrt[5]{(d-d_s)^3} \tag{5}$$

Eq.(5) is an ordinary nonlinear differential equation. For known input parameters values of i, e, f, d_s, K, A_s, n, W and S it can be solved numerically over each time step for accumulated depth d. When d is solved, the runoff rate q can be estimated according to Eq.(4).

A subcatchment usually contains different land cover types, such as roof, pavement, lawn and forest, which can generally be divided into two kinds of surfaces: impervious surface without infiltration and pervious surface which allows rainwater to be infiltrated into the soil. SWMM uses pervious subarea and impervious subarea to represent this two surfaces. The parameter *Imperviousness* is used to determine how much of the subcatchment belongs to each surface. In addition, for impervious surface, it begins generating runoff almost immediately before its depression storage depth increases. To simulate this phenomenon, the impervious surface of a subcatchment can be further categorized into two types of subareas: one subarea is with depression storage and one without. The parameter *Zero-Imperv* is used to determine fraction of the subarea without depression storage. Therefore, a subcatchment contains three sorts of subareas. Symbols A1, A2, and A3 represent the pervious subarea, impervious subarea with depression storage and impervious subarea without depression storage, respectively, and they output runoff independently of one another to the same outlet. The idealized subcatchment partitioning for runoff is shown as Figure 4-7.

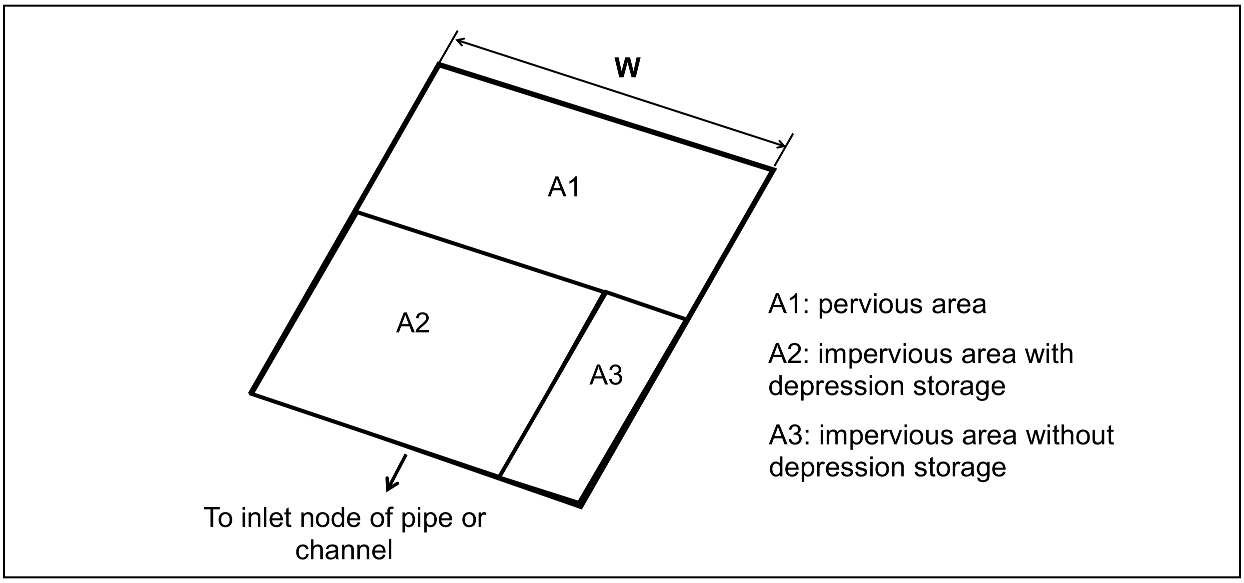


Figure 4-7: Subcatchment partitioning for runoff (Source: EPA, USA)

Based on this conceptualization, Eq.(5) for subcatchment runoff is solved individually for each subarea. Then the runoff from each subarea is combined together to generate a total runoff for the full subcatchment. The runoff equation for each subarea is solved individually based on the following conventions: 1) the same precipitation and evaporation rate in each subarea; 2) zero infiltration rate for the impervious surface; 3) different values of depression storage ds in subarea A1, A2 and A3; 4) different values of the Manning roughness in impervious surface and pervious surface; 5) the same parameter values of W and S for three subareas. The equations for each subarea are:

$$\frac{\partial d_1}{\partial t} = i - e - f - \frac{K}{n_{pv} A_1} W \sqrt{S} \sqrt[5]{(d_1 - d_{s,1})^3} \tag{6}$$

$$\frac{\partial d_2}{\partial t} = i - e - \frac{K}{n_{impv} (A_2 + A_3)} W \sqrt{S} \sqrt[5]{(d_2 - d_{s,2})^3} \tag{7}$$

$$\frac{\partial d_3}{\partial t} = i - e - \frac{K}{n_{impv} (A_2 + A_3)} W \sqrt{S} \sqrt[5]{d_3^{\ 3}} \tag{8}$$

where n_{pv} is the roughness for the pervious subarea A1, n_{impv} is the roughness for both impervious subarea A2 and A3. Note that for subarea A2, $W_2 = A_2 \cdot W / (A_2 + A_3)$ so that $W_2 / A_2 = W / (A_2 + A_3)$ and for A3, $W_3 = A_3 W / (A_2 + A_3)$ which results in $W_3 / A_3 = W / (A_2 + A_3)$. Therefore both types of impervious subareas use the same factor $W / (A_2 + A_3)$.

SWMM simulates the conveyance of a drainage system as a network consisting of nodes and links. Input flows from subcatchments enter the nodes, are conveyed in links and exit the system at outfall nodes. Figure 4-8 displays how a actual drainage system is conceptualized to a network of nodes and links of different types as mentioned in the beginning of this chapter.

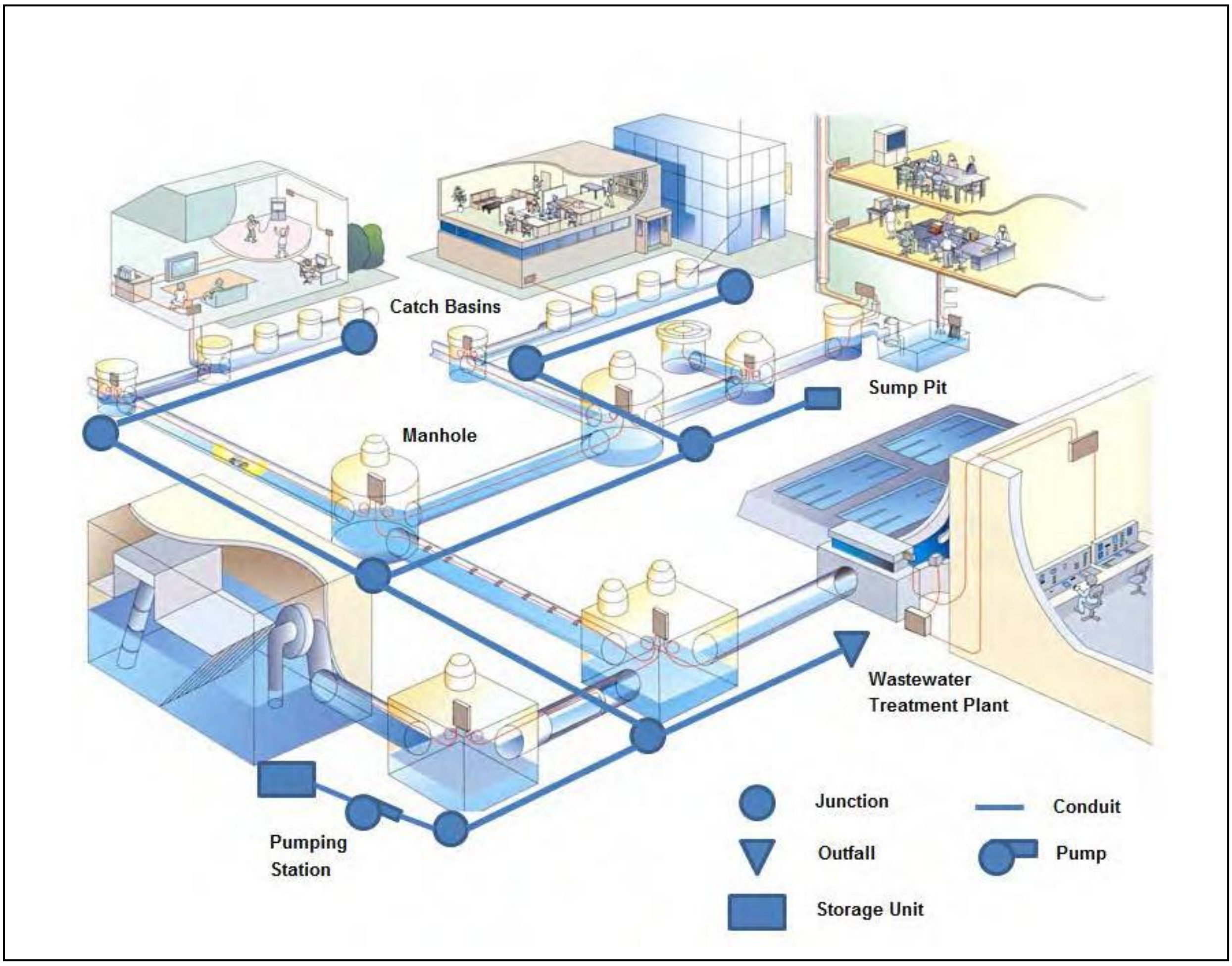


Figure 4-8: Representation of a drainage system (Source: EPA, USA)

There are three methods for the flow calculation of rainwater or flooding in channels or pipes, namely the steady flow method, the kinematic wave method and the dynamic wave method. The steady flow method assumes that the flow is constant and uniform during each calculation period, and is the simplest method. This method cannot model the storage, backwater effect, inlet and outlet loss, pressurized flow, and reverse flow. The kinematic wave method can simulate the spatial and temporal variations of flow in channels and pipes, and can be used for natural reaches with tree structures. When the time step is large, accurate simulation results can be achieved. Therefore the kinematic wave method is often used for long-term simulation (Hao, 2011; Hu, 2010). The dynamic wave method is the most accurate as well as the most complicated method for the flow calculation by solving the complete Saint-Venant equations. When the model is established, the continuity equation and momentum equation are written for channels or pipes, and the water balance equation is written for the nodes. The dynamic wave method is suitable for modeling backwater effect, inlet and outlet loss, pressurized flow, and reverse flow, on the basis of using a small time step (Hao, 2011; Hu, 2010). In this study, according to the characteristics of the above methods, combined with the purpose of this study, the kinematic wave method is used for the long-term simulation at watershed scale. The dynamic wave method is used for single storm events. The governing equations of this two methods are shown as follows:

1) The dynamic wave method

Saint-Venant equations (Eq.(9) and Eq. (10)), based on the mass conservation and momentum conservation, can describe the unsteady free surface flow through a channel or pipe. The equations are expressed as follows:

$$\frac{\partial Q}{\partial x}+\frac{\partial A_{cs}}{\partial t}=0 \tag{9}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial (Q^2/A_{cs})}{\partial x}+gA_{cs}\frac{\partial H}{\partial x}+gA_{cs}S_f=0 \tag{10}$$

Where x is distance, t is time, A_{cs} is flow cross section area, Q is flow rate, H is water head ($Z+Y$), Z is invert elevation, Y is water depth, S_f is friction slope (head loss per unit length), g is acceleration of gravity.

One can found the derivation of Saint-Venant equations from Henderson (1966), Cunge et al. (1980) and French (1985). The assumptions on which they are based contain: 1) the flow is one dimensional; 2) hydrostatic water pressure; 3) uniform slope of the channel bed; 4) using steady flow way to represent the boundary friction. In addition, the friction slope S_f can be expressed in terms of the Manning equation (Eq. (2)) used to model steady uniform flow. By combining Eq.(9) and Eq.(10), the following equation is produced:

$$\frac{\partial Q}{\partial t}=2v\frac{\partial A_{cs}}{\partial t}+v^2\frac{\partial A_{cs}}{\partial x}-gA_{cs}\frac{\partial H}{\partial x}-gA_{cs}S_f \tag{11}$$

Where v represents the flow rate, and $Q=vA_{cs}$ What's more,$A_{cs}=f(H)$, thus the desired variables are flow rate Q and water head H (or water level Y). The dynamic wave method is to solve the complete Saint-Venant equations.

2) The kinematic wave method

The kinematic wave model is derived from the same Saint-Venant equations(Eq.(9) and Eq.(10)). All variables are defined previously. Expressing head H as $Z+ Y$ (invert elevation plus water depth) and recognizing that $\partial Z / \partial x = -S_0$ (the slope of channel or pipe) update Eq.(10) to the equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2 / A_{cs})}{\partial x} + gA_{cs} \frac{\partial Y}{\partial x} = gA_{cs} (S_0 - S_f) \tag{12}$$

The kinematic wave method assumes the relation $S_0=S_f$, then：

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2 / A_{cs})}{\partial x} + gA_{cs} \frac{\partial Y}{\partial x} = 0 \tag{13}$$

That is, gravity acts as a counteract to friction.

In summary, according to the research objectives and the above equations, the hydrological simulations involved in this study mainly include subcatchment runoff simulation and drainage system flow simulation. According to the runoff transport route, it can be expressed in turn as: subcatchment- junction - conduit - outfall. The main input and output parameters of each elements and their estimation methods are shown in Table 4-1.

Table 4-1: Main parameters and estimation methods in this study

Elements	Parameters	Symbols	Units	Methods
Subcatchment	Rainfall rate	i	[in/hr]	Measured records/design storms
	Infiltration rate	f	[in/hr]	Horton equation
	Evaporation rate	e	[in/hr]	Measured records
	Area	A_s	[ac]	ArcGIS
	Width	W	[ft]	Empirical equation
	Slope	S	-	ArcGIS (based on DEM)
	Manning/roughness coefficient	n	-	Based on LULC
	Depression storage	d_s	[in]	Based on LULC
	Imperviousness	-	-	Based on LULC
Junction (node)	Invert elevation	Z	[ft]	Measured records
	Maximum depth	-	[ft]	Measured records
	Initial depth	-	[ft]	Measured records
Conduit (link)	Length	-	[ft]	ArcGIS
	Maximum depth/diameter	-	[ft]	Measured records
	Manning/roughness coefficient	n	-	Empirical values
	Bottom width	-	[ft]	Measured records
Outfall (node)	Invert elevation	Z	[ft]	Measured records

The rainfall rate i is determined from the measured precipitation data and the design storm formula based on the time step; the infiltration rate is determined according to Horton equation (Eq.(14)), where the maximum infiltration rate f_0, the minimum infiltration rate f_∞ and decay coefficient k_d are based on the soil data from HWSD estimated by SPAW (Soil Plant Air Water) software (Figure 4-9); evaporation rate e is determined based on the measured evaporation data; subcatchment area A_s is determined by ArcGIS geometry measurement tool; width W is estimated based on the empirical equation (Eq.(15)); slope of subcatchment is determined by the ArcGIS slope analysis module based on the DEM; Manning/roughness coefficient is determined based on empirical values for different land use types; imperviousness is determined based on land use data; d_s is determined by the empirical values recommended in the SWMM user manual; related parameters of junctions and conduits are determined based on the measured records. Mentioned land use data is acquired based on Remote Sensing images in this study through interpretation and classification.

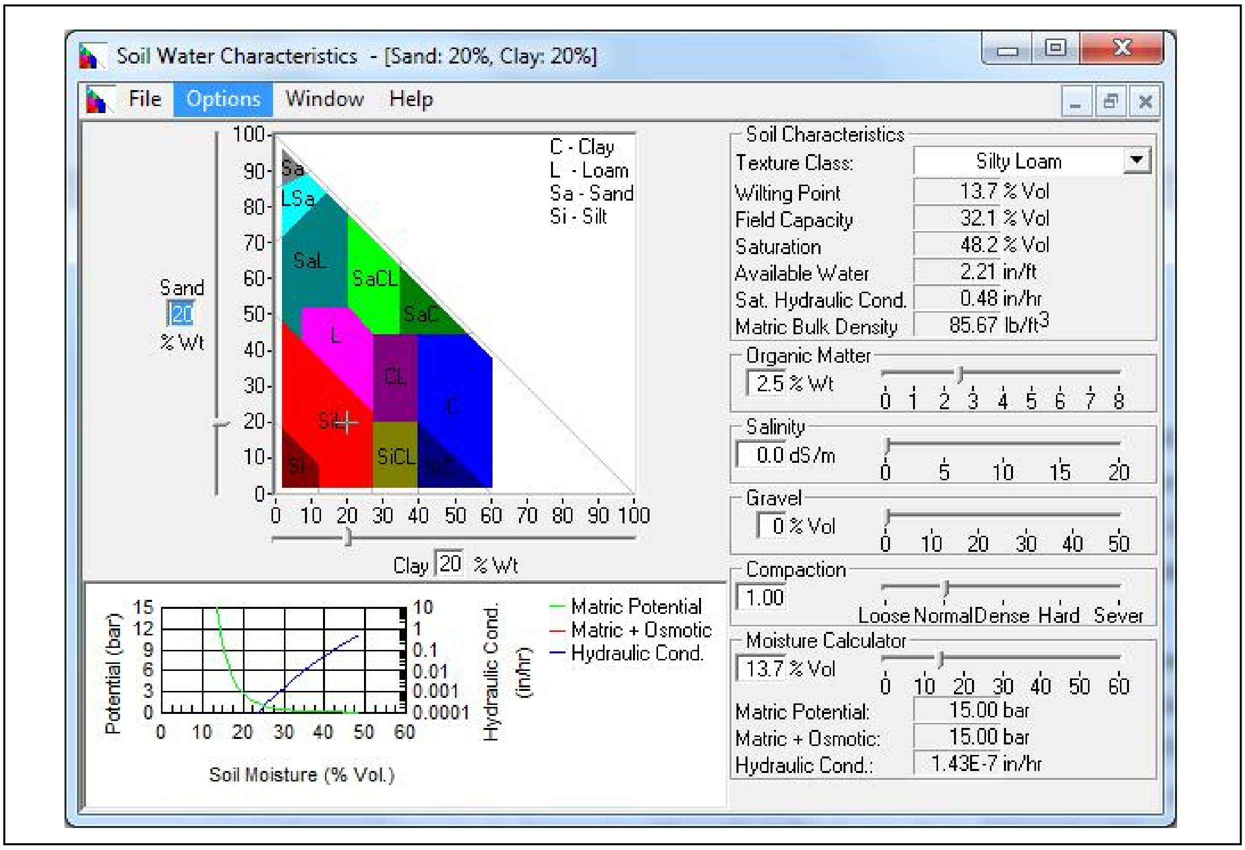
$$f = f_\infty + (f_0 - f_\infty)e^{-k_d t} \tag{14}$$

Where f is infiltration rate, f_∞ is minimum rate, f_0 is maximum rate, t is time from beginning of rainfall, k_d is decay coefficient.

$$W = K_w\sqrt{A_s}$$

(15)

Where W is Width, A_s is area, K_w is shape coefficient.



Soil Water Characteristics - [Sand: 20%, Clay: 20%]

Sand 20 % Wt

Clay 20 % Wt

Soil Characteristics

Texture Class: Silty Loam

Wilting Point 13.7 % Vol

Field Capacity 32.1 % Vol

Saturation 48.2 % Vol

Available Water 2.21 in/ft

Sat. Hydraulic Cond. 0.48 in/hr

Matric Bulk Density 85.67 lb/ft3

Organic Matter 2.5 % Wt

Salinity 0.0 dS/m

Gravel 0 % Vol

Compaction 1.00

Moisture Calculator 13.7 % Vol

Matric Potential: 15.00 bar

Matric + Osmotic: 15.00 bar

Hydraulic Cond.: 1.43E-7 in/hr

Figure 4-9: Main interface of SPAW

4.2 LIDs modeling and scenarios designing

4.2.1 LIDs conceptualizing

LID practices are modeled based on the conceptualization of the vertical layers between which SWMM tracks of how much water moves and is stored. For example, a combination of layers used to simulate Bioretention and the flow pathways between them are shown in Figure 4-10.

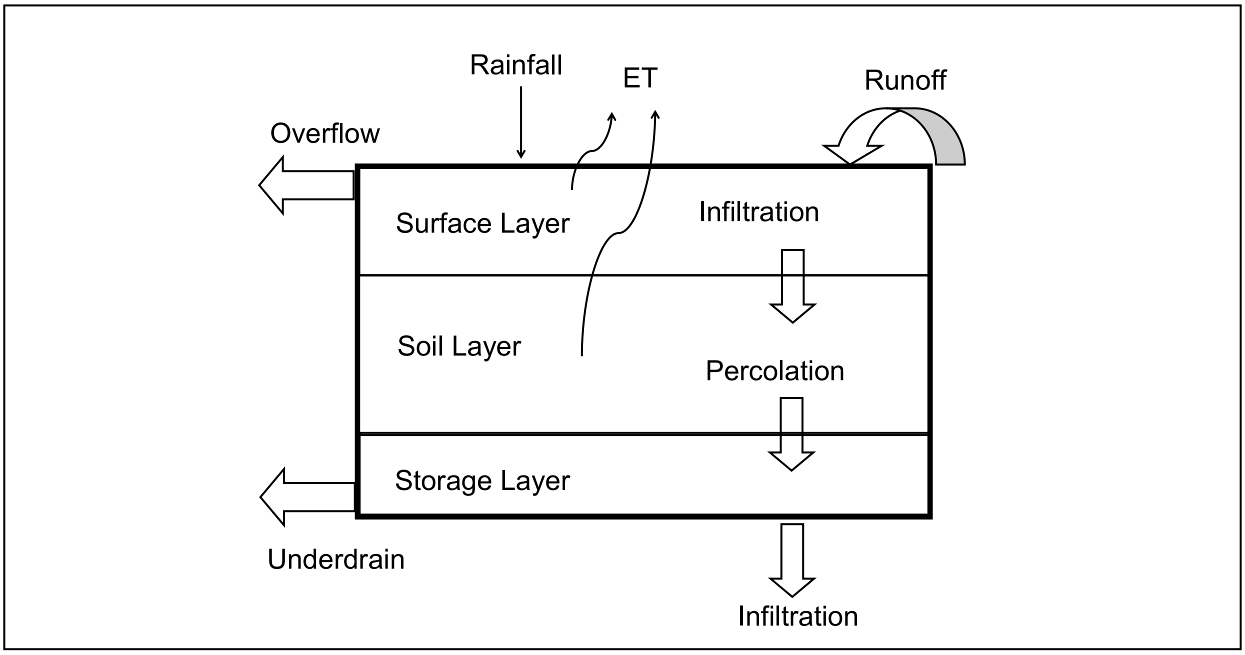


Figure 4-10: Vertical layers structure of the general Bioretention in SWMM (Source: EPA, USA)

The Surface Layer receives direct rainfall or runoff from adjacent land areas, stores excess inflow in depression storage, and generates surface outflow that either enters the drainage system or flows into adjacent land areas. The Pavement Layer is the layer of porous materials. Generally, only permeable system has this layer. The Soil Layer is the natural soil mixture or engineered soil mixture used in LIDs to support vegetative growth or provide bedding and filtration. The Storage Layer consists of crushed rocks or gravels for water storage. The Drain System output water from the Storage Layer into a common outlet channel or pipe. The Drainage Mat Layer used in green roof is a plate or mat between the soil and the roof to convey water off of the roof. Table 4-2 shows what kind of layers corresponding LIDs have (x represents required layer, o represents optional layer).

Table 4-2: Layers used to model different types of LIDs

LIDs	Surface	Pavement	Soil	Storage	Drain	Drainage Mat
Bioretention	x		x	o	o	
Rain Garden	x		x			
Green Roof	x		x			x
Permeable Pavement	x	x	o	x	o	
Infiltration Trench	x			x	o	
Rain Barrel				x	x	
Vegetative Swale	x					

There are two methods for placing LIDs in a subcatchment: 1) placing one or more LIDs in an existing subcatchment that will replace non-LID area from the subcatchment (Figure 4-11); 2) creating a new area or cut a part of original subcatchment as a new subcatchment for placing only a LID practice. The first one supports mixed LIDs to be placed in a subcatchment, each LID practice deals with a different source runoff generated from the impervious area of the subcatchment. Using this method it can not model the interaction of different LIDs (i.e., from one LID practice to another one). The second method allows LIDs to be combined in series as well as supports runoff from a non-LID subcatchment to be routed in a LID subcatchment. In this study, due to the large study area, it would spend a lot of time to partition a subcatchment for a single LID practice. Thus, the first method is adopted.

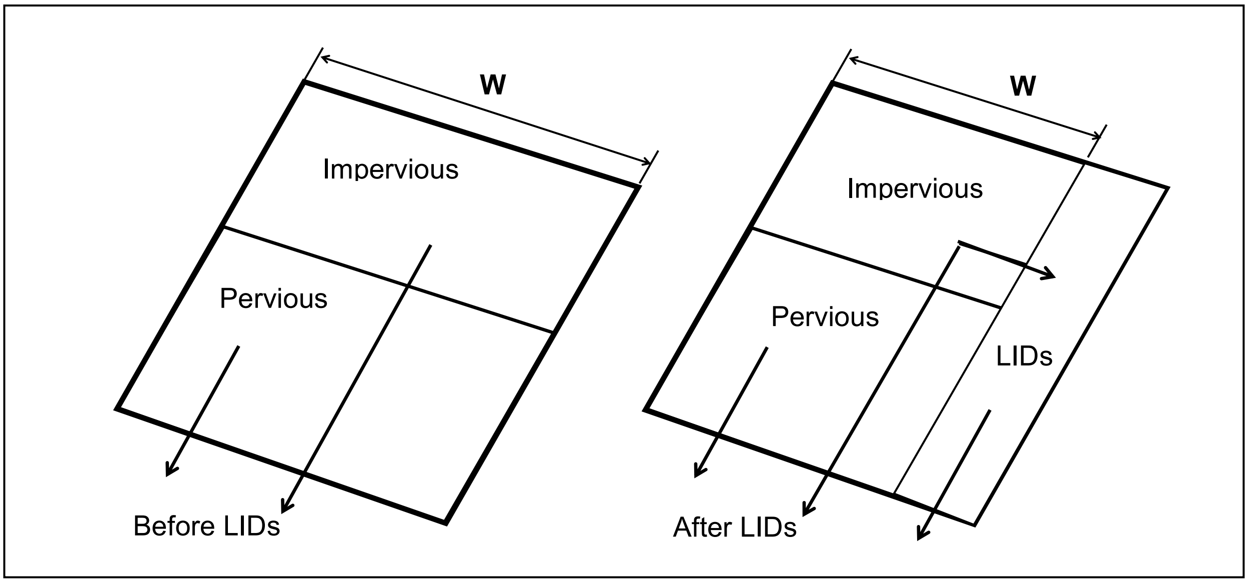


Figure 4-11: Subcatchment representation before and after LIDs (Source: EPA, USA)

4.2.2 Individual LIDs selecting for the study area

According to main functions, LIDs can generally be categorized into infiltration practices, storage practices, regulation practices, and interception practices and so on. Through the combined application of various practices, it can achieve such objectives as total runoff control, peak runoff control, runoff pollution control, and rainwater utilization. In practice, combined with the characteristics of hydrogeology and water resources in different regions, LIDs and combined systems should be selected in accordance with local conditions and economical and efficient principles. Table 4-3 summarizes the abilities of individual LIDs according to indicators such as functionality, cost, and landscape (MOHURD, 2014).

Table 4-3: Summarry of the capacity of individual LIDs

LIDs	**Functionality**			**Economy**	**Landscape**
	Runoff volume	Runoff peak	Runoff pollution		
Bioretention	●	◎	●	◎	●
Rain Garden	●	◎	◎	●	●
Green Roof	●	◎	◎	○	●
Permeable Pavement	◎	◎	◎	○	○
Infiltration Trench	◎	○	◎	◎	○
Rain Barrel	●	◎	◎	●	○
Vegetative Swale	●	○	◎	●	●

● Good ◎ General ○ Poor

In chapter 3, the water risks faced by the study area have been introduced. Among them, urban floods and waterlogging are currently the most prominent problems. The main reasons are the larger impervious area caused by the high intensity of land development and the infrastructure defects due to the lack of construction experience in early development phase of China. As shown in Figure 3-4, 3-5 and 3-6, in many cities of China, especially in the old districts, rainwater pipes in many residential areas directly discharge roof rainwater to the roads, and serious missing of vegetation layer has occurred in landscape flower beds, and unrepaired pavement exits in almost each residential area. Using the conventional methods, a lot of time and money need to be invested in rebuilding or renovating these facilities, such as connecting roof downspouts to urban drainage systems, replanting vegetation layers and paving new roads, etc. With the introduction of LID concept, according to the characteristics of different LIDs, it will be more effective to apply them to the transformation of old urban areas, such as adding Rain Barrels connected with roof downspouts to directly collect rainwater from the roof for utilization (Figure 4-12), landscape flower beds into Rain Garden (Figure 4-13), and transforming damaged pavements into Permeable Pavements (Figure 4-14).

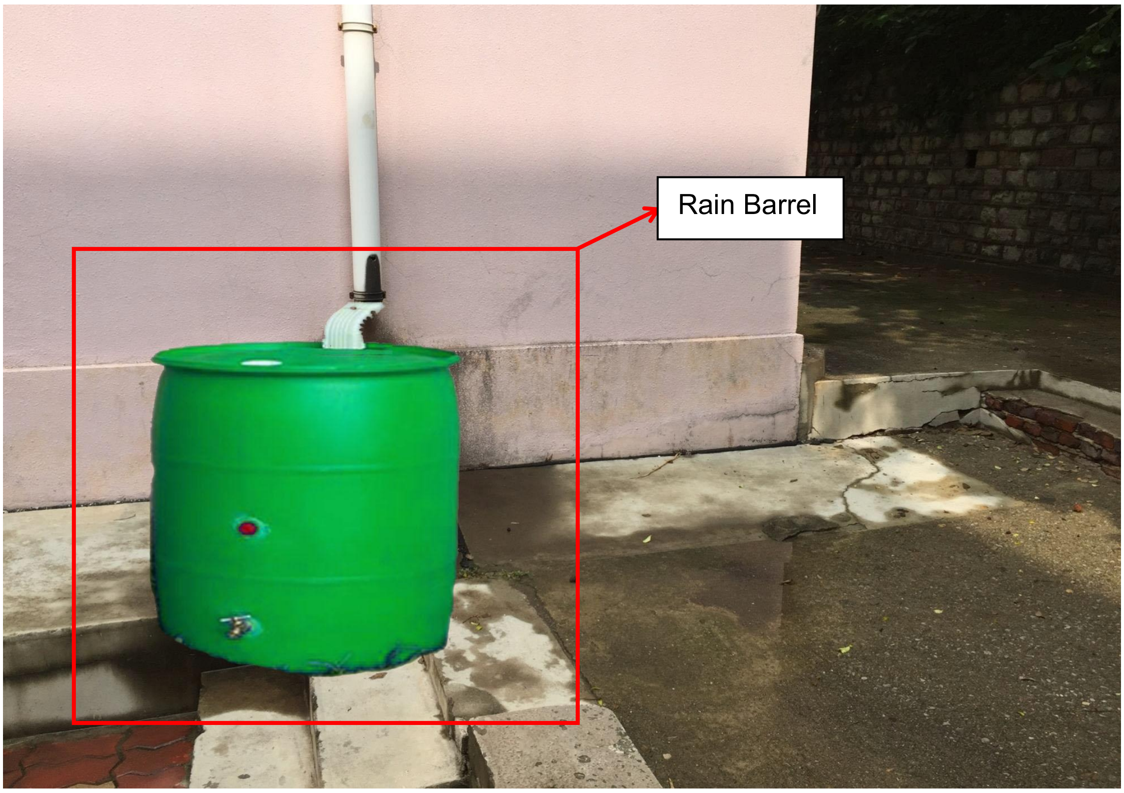


Figure 4-12: Rain Barrel connected with the roof downspout (Source: WRISD, China)

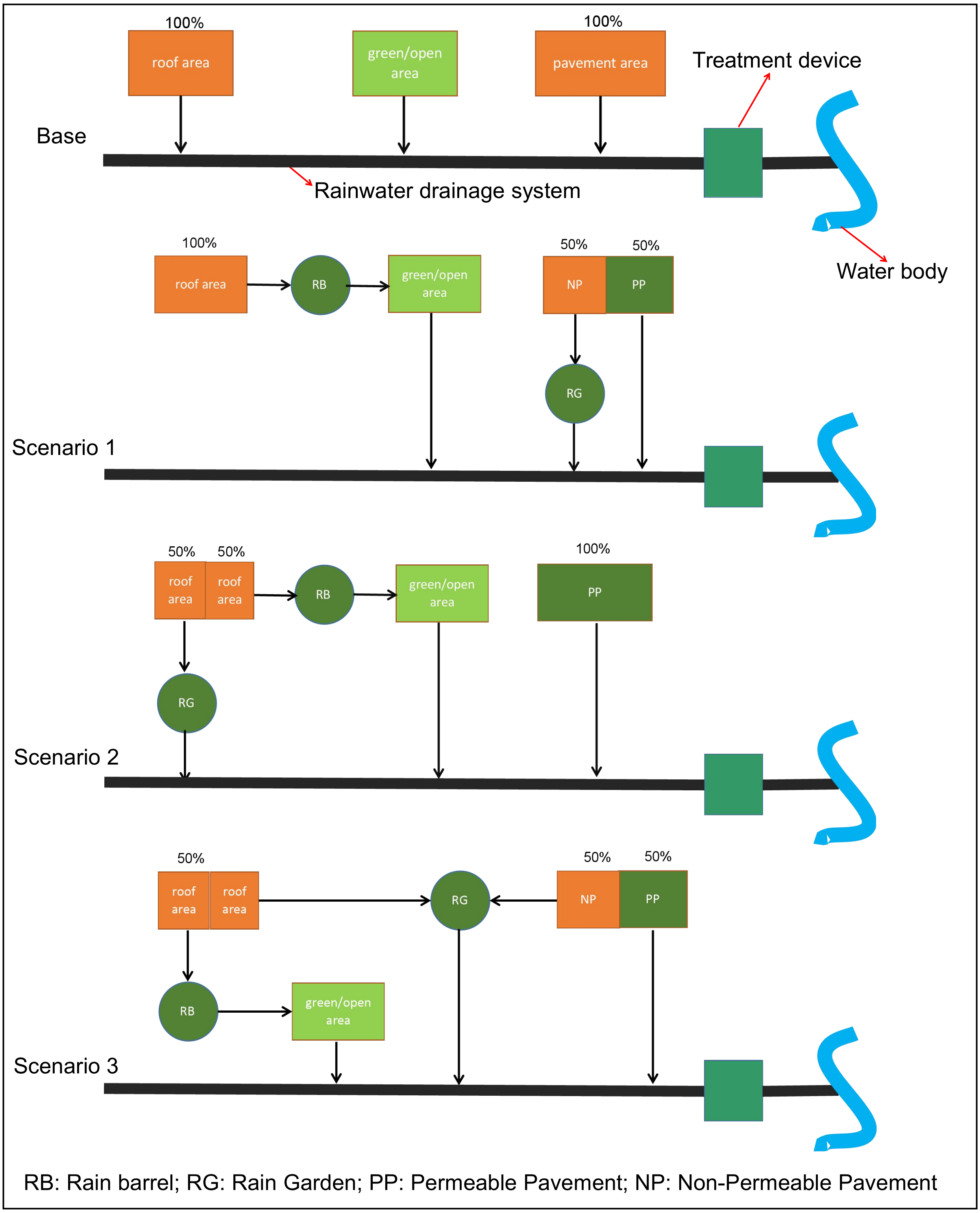
Figure 4-13: Placement of Rain Garden (Source: WRISD, China)

Figure 4-14: Permeable Pavement replacing the damaged road pavement (Source: WRISD, China)

Therefore, based on the characteristics of LIDs shown in Table 4-3 and the major problems faced by the study area, taking the total runoff and runoff peak control as objectives and meanwhile considering economy and landscape, in this study, Rain Garden, Permeable Pavements and Rain Barrel are used as basic LIDs.

4.2.3 Scenarios designing of combined LIDs and extreme storms

Many engineering practices of LID have been designed and their respective effectiveness has also been determined. However, for a mixed LULC (Land Use/ Land Cover) area with multiple LIDs (LID practices), the effectiveness on the whole area is still not comprehensive because of mentioned limitations and variety of LIDs. In order to avoid the rainwater management measures being onefold, designing a combined LIDs solution can not only effectively achieve control objectives, but also save costs. In this study, according to the input and output paths and ratios of treated impervious surface and the characteristics of LIDs (Rain Garden, Permeable Pavement, Rain Barrel), three scenarios (Figure 4-15) with different combinations and layouts of LIDs were established to compare their respective effectiveness on controlling runoff volume and peak. Note that there is no hydraulic link between the LIDs. each LID practice only processes runoff from different proportions of impervious surfaces and the runoff or overflow is discharged into the drainage systems. Generally, overflow from the rain barrel will be discharged into the nearby green space.



RB: Rain barrel; RG: Rain Garden; PP: Permeable Pavement; NP: Non-Permeable Pavement

Figure 4-15: Base and scenarios designing of combined LIDs

Scenario 1 assumes that 100% of the roof runoff enters the Rain Barrels, 50% of the pavement runoff runs into the Rain Gardens, 50% of the pavement runoff passes through the Permeable Pavement, and all finally run into the urban rainwater system; Scenario 2 assumes that 50% of the roof runoff enters the Rain Barrels, 50% of the roof runoff enters the Rain Gardens, 100% of the pavement runoff flows through the Permeable Pavement, and all finally enter the urban rainwater system; Scenario 3 assumes that 50% of the roof runoff enters the Rain Barrels, 50% of the roof runoff and 50% of the pavement runoff runs into the Rain Gardens, 50% of the pavement runoff flows through the Permeable Pavement, and all eventually enter the urban rainwater system. Three scenarios were imported into the SWMM model for simulation.

The design storm is the basis of the design of the drainage system. In addition to the average storm intensity within a certain duration, the time-distributed form, i.e. the rainfall pattern, is also an important factor. For rainfall pattern in Jinan, this study uses the Chicago model widely used at developed counties as suggested by Cen et al. (1998). This rainfall pattern, in the rainfall intensity calculation model representing the maximum average intensity rule of the same frequency, introduces the average shape and intensity peak position, and can obtain the average rainfall intensity, time-interval rainfall intensity and instantaneous rainfall intensity. The model described by the instantaneous intensity summarizes the special rainfall patterns, forming a rainfall pattern that more fully reflects the characteristics of storms.

The Jinan City Municipal Engineering Design and Research Institute revised the formula for urban storm intensity in Jinan according to the rainfall data from 1960 to 1990 using the analytical method as follows:

$$\bar{i} = \frac{11.197(1+0.7573\lg P)}{(\Delta t+11.091)^{0.6645}} \tag{16}$$

Where $\bar{i}$ is average intensity (mm/min)， P is recurrence interval(a)； $\triangle t$ is rainfall duration(min)；

The recurrence intervals of 1-year, 3-year, 10-year, and 100-year respectively, the rainfall duration of 1-hour, 2-hour, and 4-hour are used as basis, leading to 12 design storm scenarios. The Chicago model is a single-peak curve, the relative position of the peak is represented as r, the rainfall duration before the peak is Δt_b, the corresponding instantaneous rainstorm intensity is i_b; the post-peak rainfall duration is Δt_a, and the corresponding instantaneous rainstorm intensity is i_a, Where $\Delta t = \Delta t_b + \Delta t_a$. The general design standard in China for rainfall peak is less than 0.5 (Cen et al. 1998). In this study, r = 0.3. The instantaneous storm intensity formulas are introduced as follows:

$$i_b = \frac{\alpha\left[\dfrac{t(1-0.6645)}{r}+11.091\right]}{\left[\dfrac{t}{r}+11.091\right]^{0.6645+1}} \tag{17}$$

$$i_a = \frac{\alpha\left[\dfrac{t(1-0.6645)}{1-r}+11.091\right]}{\left[\dfrac{t}{1-r}+11.091\right]^{0.6645+1}} \tag{18}$$

Where $\alpha = 11.197(1+0.7573\lg P)$, t is instantaneous time. Rainfall intensity curves of designed storms in this study are shown as Figure 4-16.

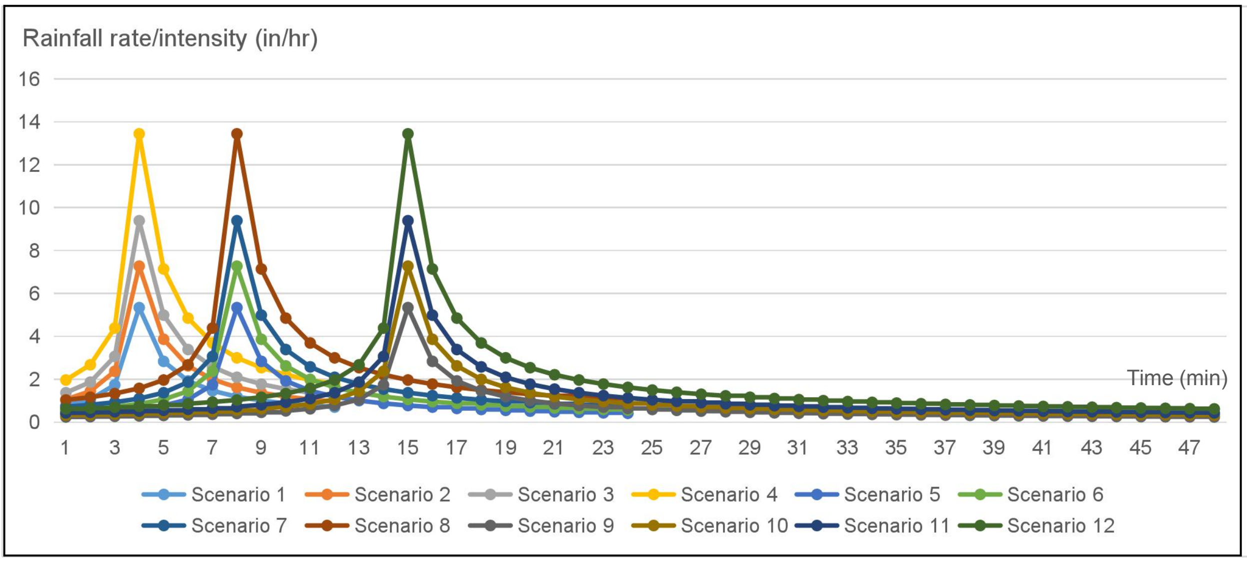


Figure 4-16: Rainfall intensity curves of designed storms

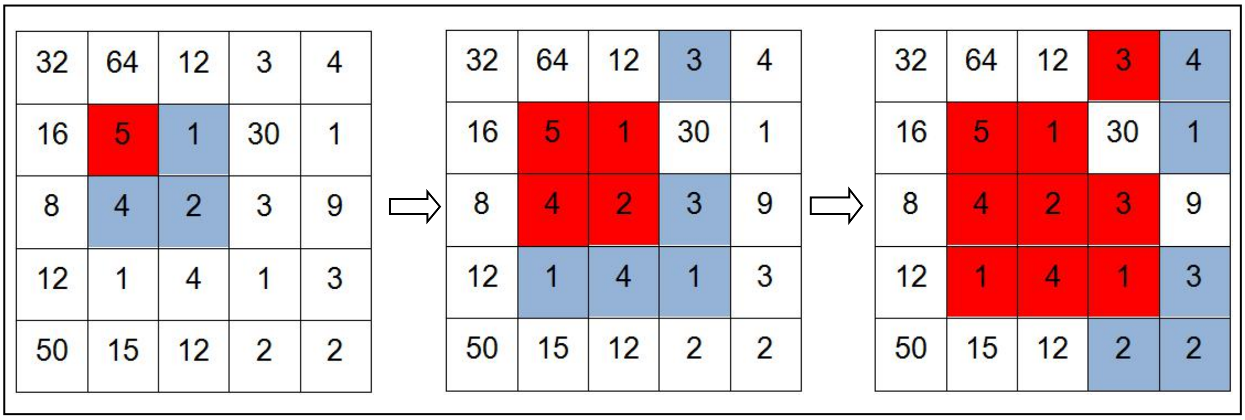
4.3 Evaluation of LIDs based on the visualized scene

4.3.1 Inundated area estimation

LID efficiency evaluation is generally expressed by using the reduction rate of runoff or flood characteristics, such as runoff volume or peak, or economic efficiency. Based on this results, professionals such as from the departments of water supply and drainage design or flood management can quickly obtain information, but for cross-disciplinary professionals such as urban planners, government managers, or the public, this statement is not so easy to understand. In addition, since the design of urban drainage systems is often based on a certain recurrence interval, if the design is renewed for 20-year or 50-year, even if the perfect drainage system is not able to defense the extreme storm with a 100-year recurrence interval. To discharge extra flood, the road may be used as a temporary flood discharge channel. Therefore, to study the effect of LID encountering the extreme storm, the flooded area or Inundated area can be used as the metric, such as the change of inundation area before and after using LIDs.

SWMM can simulate the flood flow curve at the overflow point, which can be used as the initial condition of the shallow water equation. Theoretically, the inundation simulation of 2D flooding can be performed based on the shallow water equation using the finite difference method. The flow velocity of each grid can be accurately simulated. That is, dynamic flooding process can be performed to determine the inundation area. However, due to the limitation of boundary conditions, complex calculation, long time-consuming and demanding high-resolution DEM data, It is difficult to implement quickly. In this study, seed algorithm is used to determine inundated area. Based on the simulation results of design storm scenarios with different recurrence intervals and duration, the locations of flood overflow nodes and overflow volume are determined. Then, the inundated area is estimated based on the DEM and seed algorithm. The LID scenario is brought into the SWMM model to simulate, and then the new overflow nodes and overflow volumes are determined, and the same method is used to determine the inundation area. To convert a numerical quantity into an intuitive and visual graphical representation will help non-professionals to quickly obtain information. This method can not model a dynamic flood submergence process, but the final submergence range is the same as that obtained with the shallow water equation.

The seed algorithm is described as follows: first, compared to the actual terrain, each grid of DEM represents a uniform elevation, each connected state is terrace-like (assuming that water can accumulate without boundary constraints); Elevation of the grid in which overflow node is located as a seed point, compared with its neighboring eight grids'. As long as the elevation of the seed point is greater than others', the grids with less elevations will be filled with overflow flood at the same time. Due to the need to fill according to the total overflow flood volume, filling priority must be considered for the allocation of water. Priority to fill the grid with the maximum elevation difference (because of the greater the difference between grids, the greater the slope, the greater the flow rate), and so on, until all eight adjacent grids with lower elevations are filled, or the overflow flood volume is completely used up; (2) after all adjacent grids are filled, their water levels are equal to the elevation of the seed point. As a whole with the seed point, a new seed area will be formed as basis, then using the same method in step (1) to fill the grids adjacent to the new area, and so on, the final inundated area will be generated. Note that when the elevations of all grids adjacent to the seed point are larger than the seed point's, a grid with the smallest difference in elevation from the seed point will be selected, and is used as the seed point, according to the elevation difference, to calculate again, and so on. Figure 4-17 shows the process.



32	64	12	3	4
16	5	1	30	1
8	4	2	3	9
12	1	4	1	3
50	15	12	2	2

⇨

32	64	12	3	4
16	5	1	30	1
8	4	2	3	9
12	1	4	1	3
50	15	12	2	2

⇨

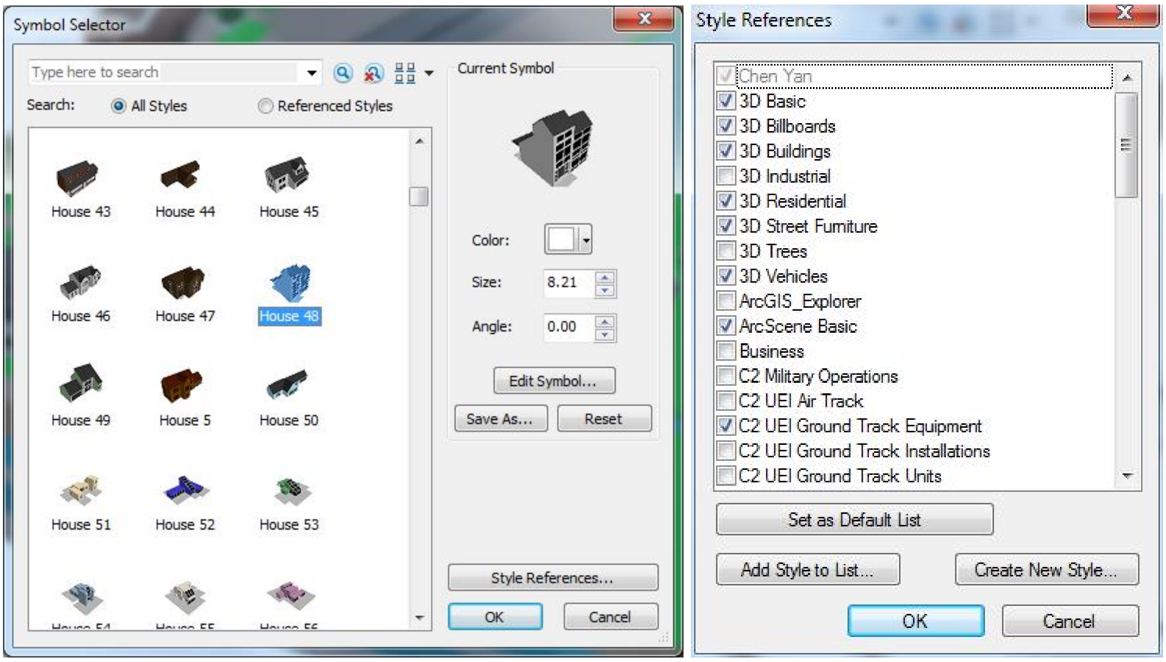
32	64	12	3	4
16	5	1	30	1
8	4	2	3	9
12	1	4	1	3
50	15	12	2	2

Figure 4-17: Basic process of the seed algorithm

4.3.2 Building of 3D scene

3D (three dimensional) scene has been applied to many fields such as interior design, game development and digital city. However, the building of a 3D scene often requires to build 3D element models, such as buildings, trees, etc., and requires the use of professional software, such as 3D-max or Maya, so that the professionalism and complexity are multiplied. In the natural sciences, the use of 3D scene is less. With the development of Remote Sensing and surveying and mapping technology, the basic GIS database in many counties has been improved, and batch 3D modeling using GIS data begins to be used gradually.

In this study, 3D module of ArcScene was used to build the 3D scene of the study area. ArcScene integrates a lot of general 3D scene elements, as shown in the Figure 4-18, and users can establish 3D scenes by firstly creating point features and then symbolizing into 3D scene elements. However, this method cannot describe the situation of the study area flexibly and truly, and it is difficult to control the size of the elements. In order to reflect the real scene of the study area, first to use ArcScene, according to the attribute features of basic GIS data, such as building height, width, etc., by setting the base height and stretching method, a basic 3D scene will be built. Then, to import the 3D scene into Sketchup (a 3D modeling software, as shown in Figure 4-19) for texture handling using actual photos of elements. At last, to export from Sketchup to AcrScene for rendering. Based on the established 3D scene and the inundated area generated by the method described in section 4.3.1, a dynamic flooding process will be displayed using animation rendering method of ArcScene.



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☑ Chen Yan
☑ 3D Basic
☑ 3D Billboards
☑ 3D Buildings
☐ 3D Industrial
☑ 3D Residential
☑ 3D Street Furniture
☐ 3D Trees
☑ 3D Vehicles
☐ ArcGIS_Explorer
☑ ArcScene Basic
☐ Business
☐ C2 Military Operations
☐ C2 UEI Air Track
☑ C2 UEI Ground Track Equipment
☐ C2 UEI Ground Track Installations
☐ C2 UEI Ground Track Units

Figure 4-18: 3D elements of ArcScene

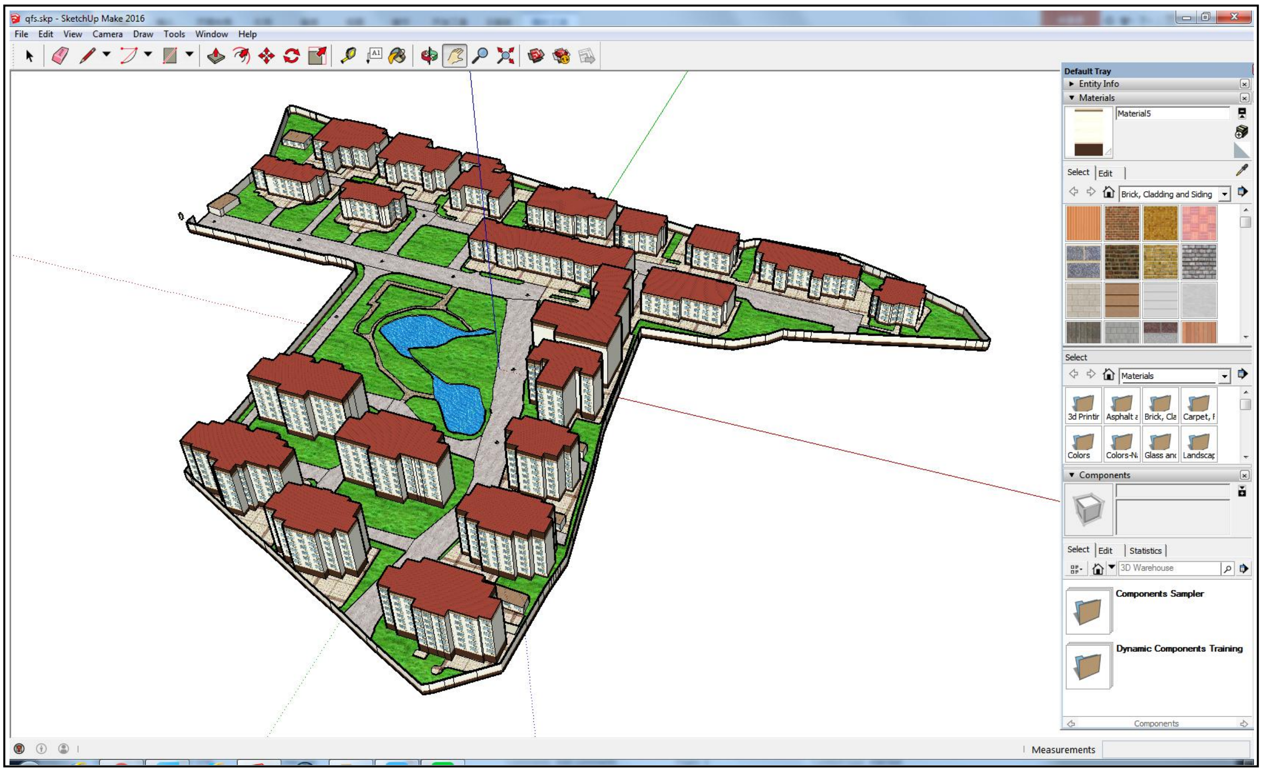


Figure 4-19: Texture painting for 3D elements in SketchUp

5. Results

5.1 Building of SWMM

5.1.1 Subcatchment discretization

Subcatchment discretization first needs to determine the distribution of the rivers or channels, and then determine their subcatchments according to the corresponding streams. In this study, due to the lack of large-scale topographic map, a DEM with a spatial resolution of 30m was used to extract the main rivers of the subcatchments through flow direction analysis. This step was performed in ArcSWAT. Figure 5-1 shows the actual rivers and the extracted rivers produced based on ArcSWAT and DEM. As most of the the study area lie in plain area, the extracted rivers and the actual rivers matches well in the upstream mountainous area, while the downstream plain area has relatively errors (as shown in Figure 5-1). In addition, due to artificial reconstruction, some natural rivers have been transformed or constructed, having impacts on extraction.

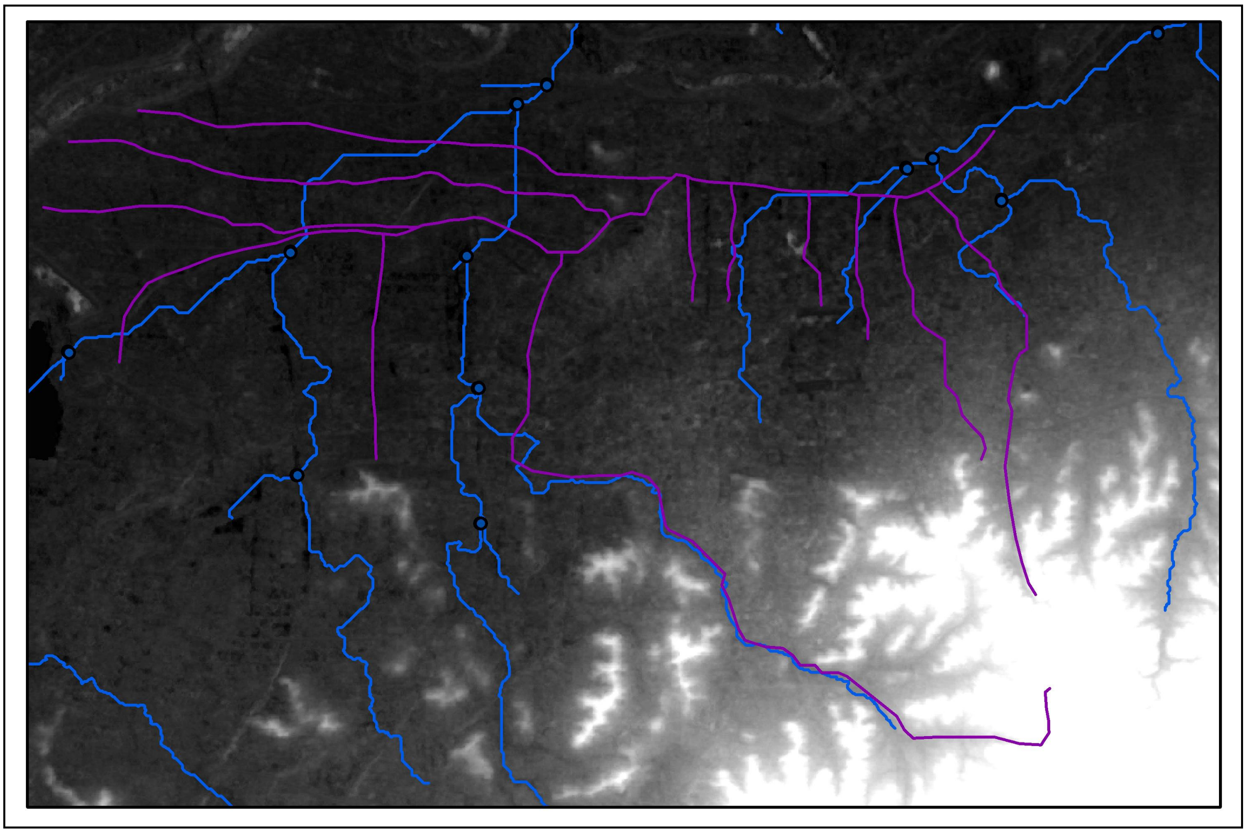


Figure 5-1: The actual rivers (purple) and the extracted rivers (blue)

In ArcGIS, with the actual rivers as reference, the extracted rivers were forced to be calibrated by a manual correction method, and outlets of the tributaries and main streams were added. The calibrated rivers were imported into ArcSWAT for subcatchment discretization. The result is shown in Figure 5-2.

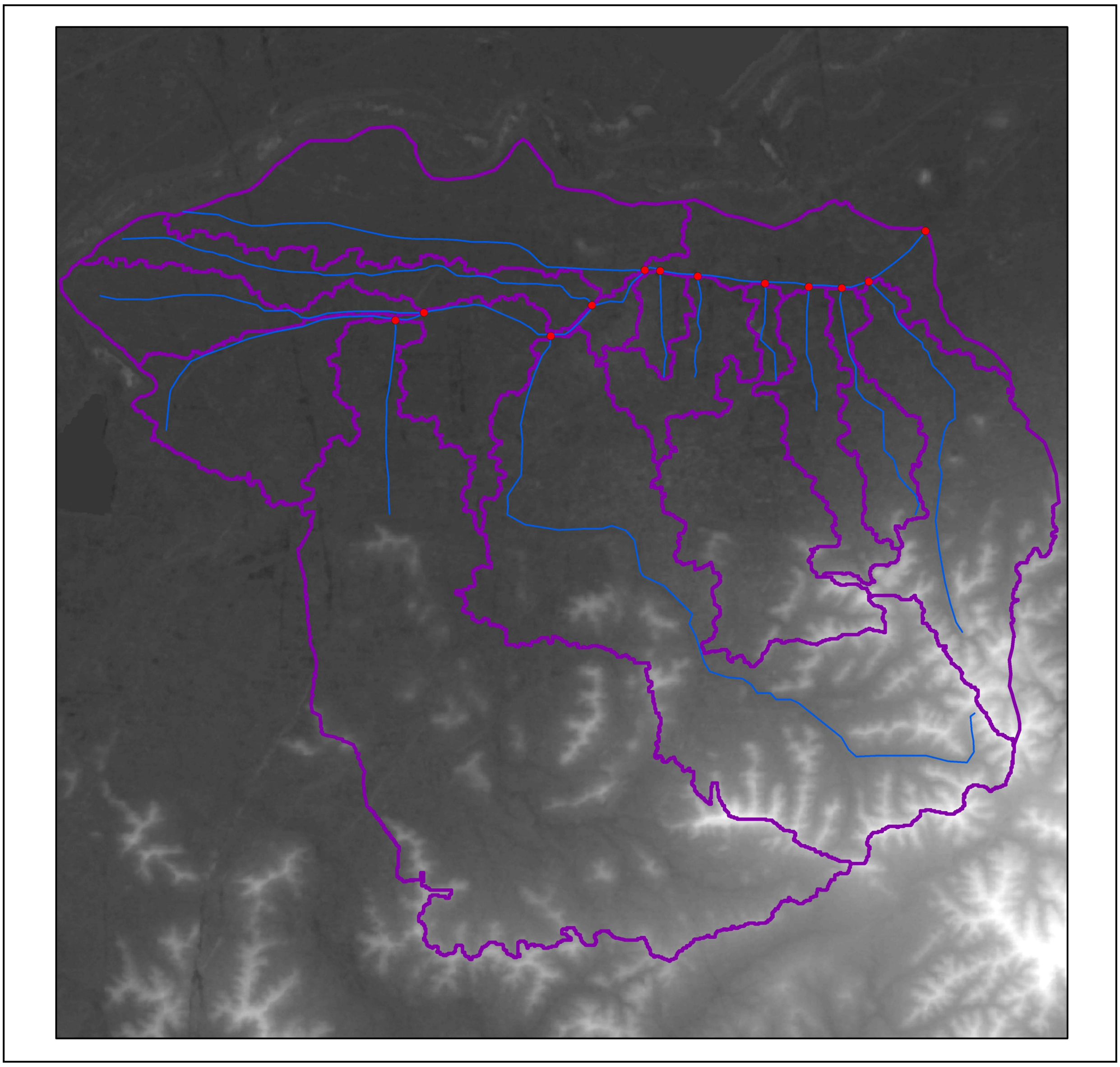


Figure 5-2: Subcatchments, main rivers and outlets in the study watershed

The study watershed was divided into 15 subcatchments. According to the status that the subcatchment runoff is conveyed to the main reaches, nodes were added to the main reaches, and the nodes divides the main reaches into several links. Those nodes and links are known as junction objects and conduit objects in SWMM. Finally, 11 junctions, 1 outfall, and 11 conduits were created. After the decoration in ArcGIS they are shown in Figure 5-3. Runoff from subcatchment S1 and S2 is finally discharged to the junction J1, and J2 receives the runoff from subcatchment S3 and outflow from conduit C1, and J3 receives the runoff from subcatchment S4 and S5 and outflow from

Conduit C2, and so on, until the total runoff is discharged to the outfall O1.

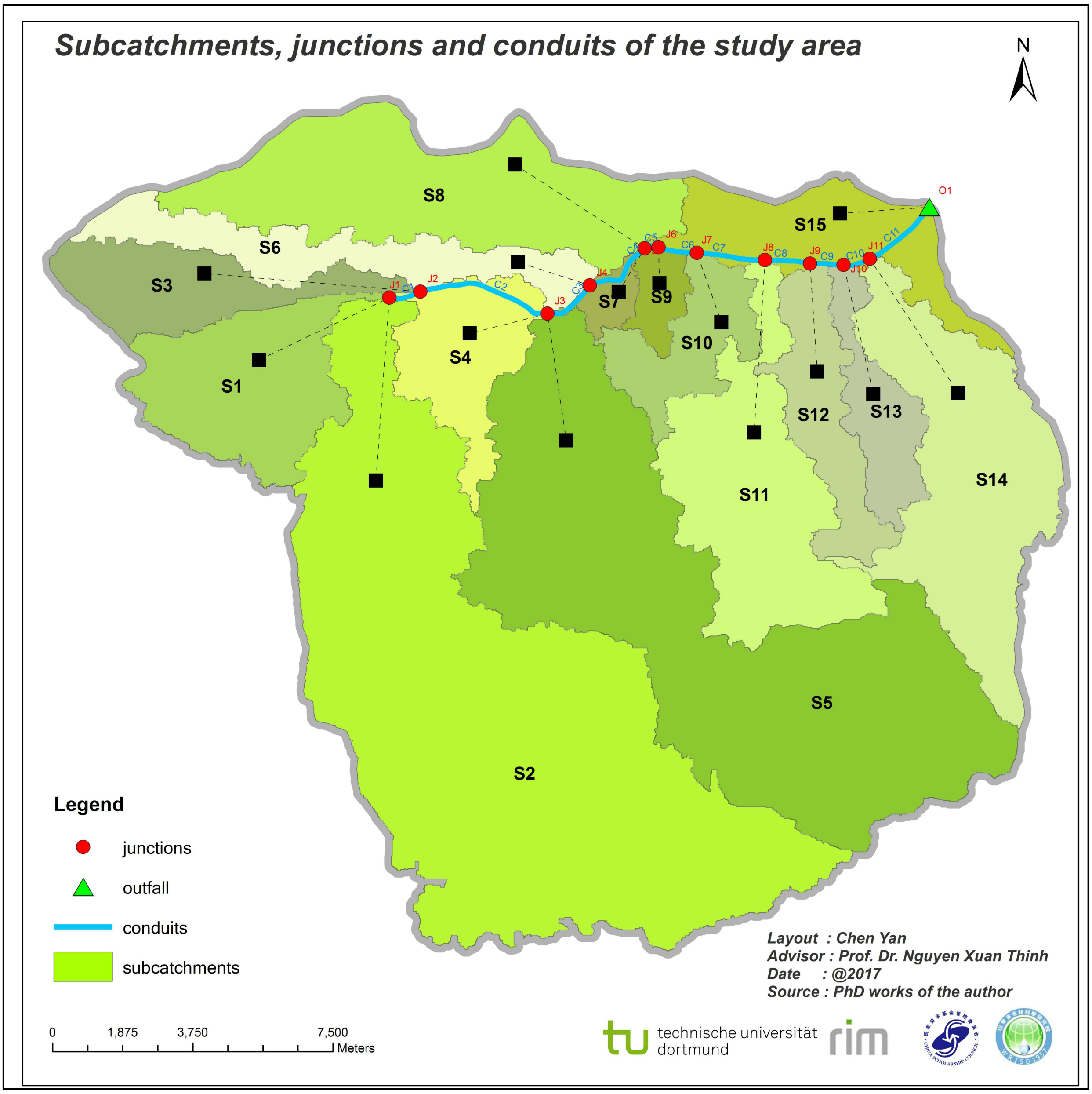


Figure 5-3: Subcatchments, junctions and conduits of the study area

5.1.2 Land cover and land use classification

Change in land cover and land use, to a certain extent can reflect the process of urbanization, such as change in urban area or impervious area. In addition, in SWMM, many input parameters need to be determined based on the type of land use, such as imperviousness, Manning coefficient and depression storage (see chapter 4, Table 4-1). Due to the lack of spatial databases with long-term records in most cities of China, and the low level of data sharing, historical land cover and land use data are difficult to be obtained. This study used the digital image processing method to extract land cover maps of the study area based on ENVI and remote sensing images. Landsat images with good quality and season similarity from the USGS Explorer, in 1979, 1989, 1999, 2009 and 2017, were downloaded. Using the maximum likelihood method belonging to the unsupervised classification method of ENVI, the urban area and non-urban area were initially classified by selecting samples. The separation coefficient of samples reaches 90%. Results were calibrated using high-resolution historical aerial imagery provided by the Google earth. Figure 5-4 shows the land cover maps of the study area in 1979, 1989, 1999, 2009 and 2017. The area and percent of urban area are shown in Table 5-1.

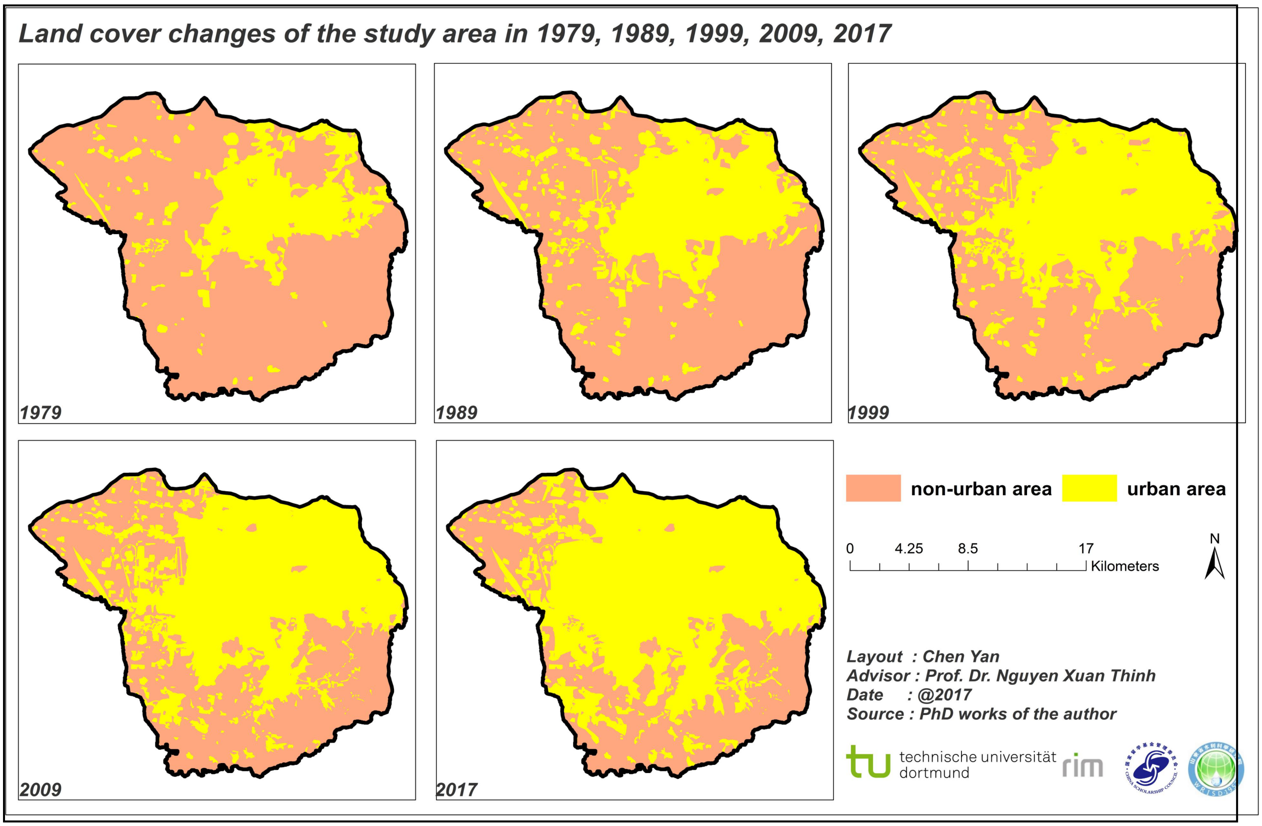


Figure 5-4: Land cover of the study area in 1979, 1989, 1999, 2009, 2017

Table 5-1: Changes in urban area and non-urban area of the study area

Period	Urban area [km^2]	Non-urban area [km^2]	Percent of urban area [*100%]
1979	88.82	308.59	0.22
1989	138.28	259.13	0.35
1999	174.91	222.50	0.44
2009	212.64	184.77	0.54
2017	248.46	148.95	0.63

Urbanization rate is a measure of urban development. Population statistics is generally used to describe it, that is, the proportion of urban population in the total population (including agricultural population and non-agricultural population). According to statistics from the National Bureau of Statistics of China, the urbanization rates in Jinan in 1979, 1989, 1999, 2009, and 2017 are 23.00%, 39.47%, 49.13%, 63.72%, and 70.53%, respectively. The trends of urbanization rate and percent of urban area are closely as shown in Figure 5-5. The growth rate is the largest between 1979 and 1989. The probable reason for that might be due to the implementation of Reform and Opening policy of China since 1978, the economic vitality was increasing, and the urban development in this stage was rapidly. The decrease in the growth rate from 1989 to 1999 might involve political factors and international turmoil. After 1999, it shows a growing trend, but the growth rate decreases again from 2009 to 2017. It might be considered that as the sustainable development proposed, in order to limit the population leap forward and ensure the urbanization and urban infrastructure construction be consistent, the government issues relevant regulations or policy for unchecked growth of the population. In addition, the development of new rural construction policy in China during this period might also have a certain effect on the results. The results indicate that urban area change could be used as a measure of urbanization in the study area.

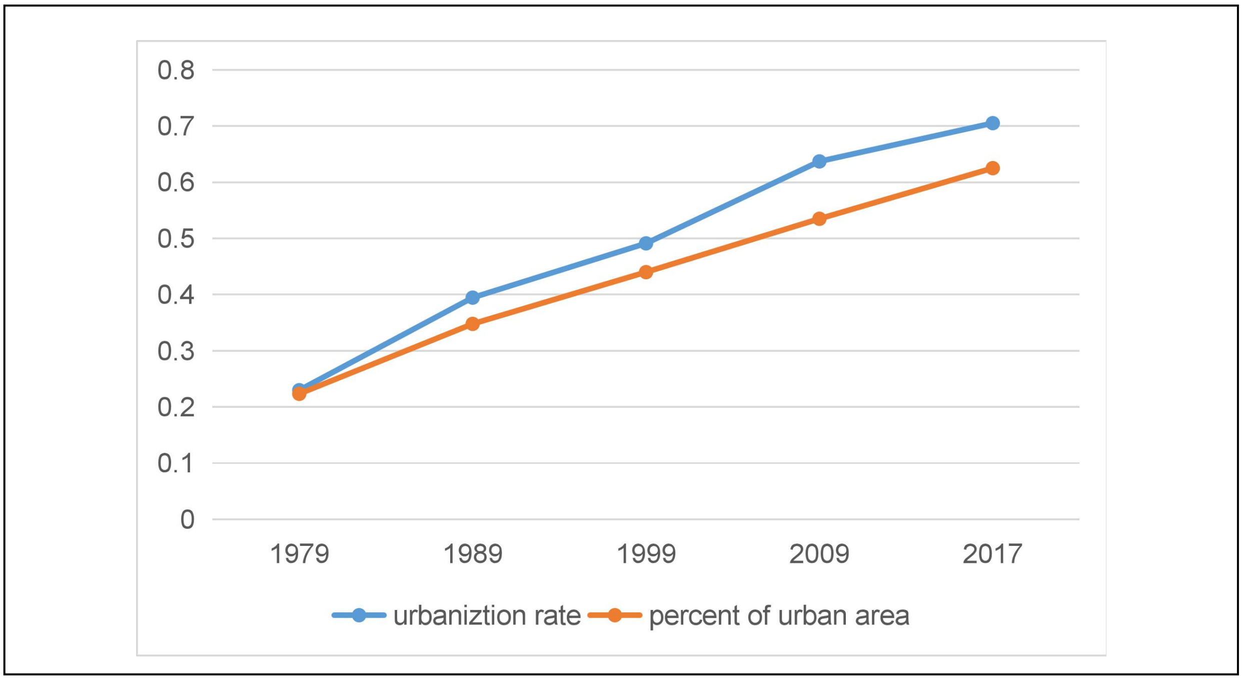


Figure 5-5: Urbanization rate and percent of urban area of the study area

In urban planning and construction, the type of land use in built-up area would not change in a large area in the long term, except for natural disasters, such as reconstruction after extensive earthquake or tsunami damages. According to the statistical yearbook data analysis, the land use in the built-up area of the study area remained basically unchanged in the past 30 years, and the latest urban planing (until 2020) focused on the layout of the new development area. Therefore, based on the land cover maps classified above and the urban planning map of the study area (2020), the land use classification of the study area was determined using the spatial overlay analysis method of ArcGIS, as shown in Figure 5-6. The type of land use is based on the "China Land Use Classification Standard”. Note that the change characteristics of land use are not the main research objective of this study. As the basic condition of SWMM parameter estimation, it is adequate to determine the type and distribution of land use.

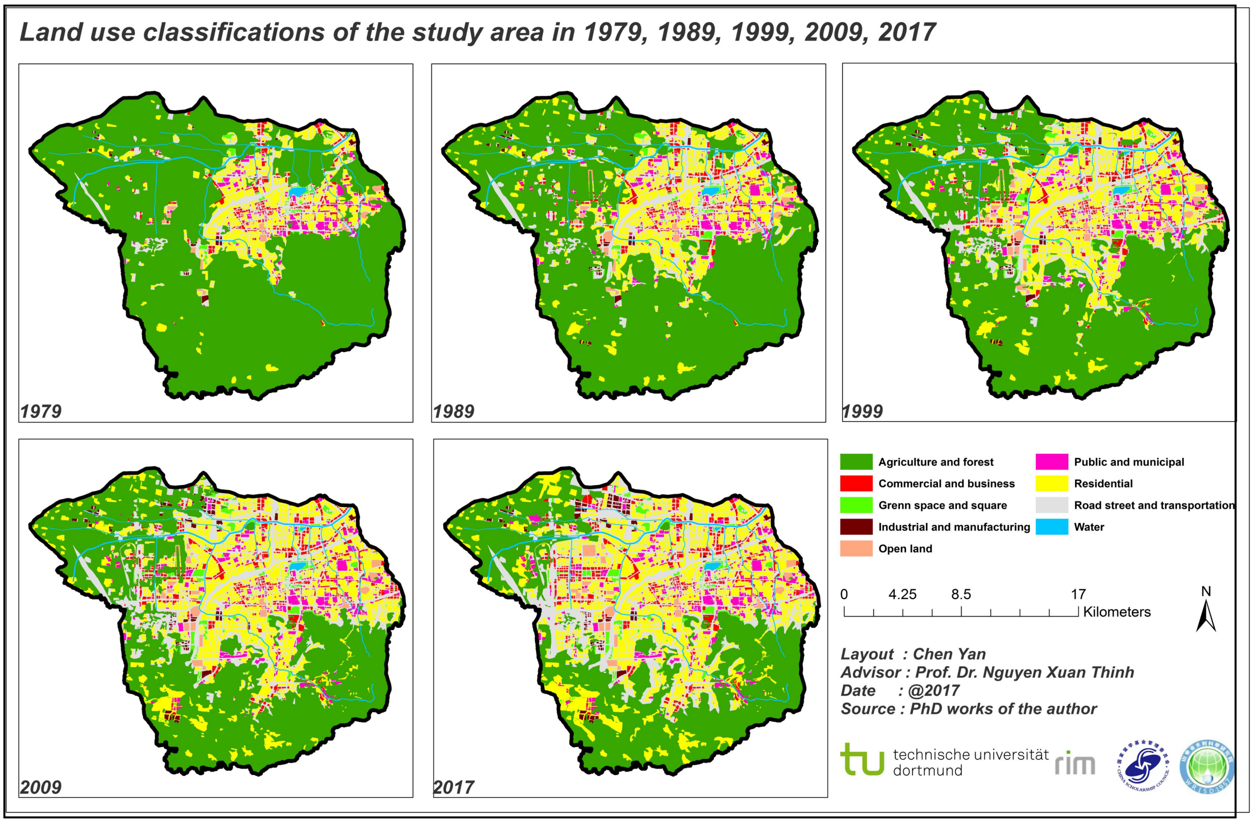


Figure 5-6: Land use classifications of the study area in 1979, 1989, 1999,2009, 2017

5.1.3 Parameter estimation

Table 4-1 in chapter 4 shows the parameters and their estimation methods of SWMM elements. For the element of subcatchment, the rainfall intensity was obtained from observation data and design storms. The infiltration rate was determined by the Horton equation. The equation needs to first determine the maximum infiltration rate and minimum infiltration rate. The minimum infiltration rate is approximately equal to the saturated hydraulic conductivity of the soil. The maximum infiltration rate is recommended by the SWMM User Manual based on the soil characteristics. According to the soil map (Figure 5-7, left one) and the soil characteristics (as shown in Table 5-2) provided by HWSD, SPAW was used to determine the soil texture and saturated hydraulic conductivity (Table 5-2 and Figure 5-7, right one). In addition, since some subcatchments contain at least two types of soil, the area-weighted method was used to determine the average minimum permeability of those subcatchments.

Table 5-2: Soil characteristics, texture and saturated hydraulic conductivity

Symbol	Name	Sand [%]	Silt [%]	Clay [%]	Texture	Saturated hydraulic conductivity [in/hr]
FLc	Calcaric Fluvisols	34	48	18	Loam	0.13
ATc	Cumulic Anthrosols	29	50	21	Silty Loam	0.26
CMc1	Calcaric Cambisols	36	43	21	Loam	0.13
GLk	Calcic Gleysols	41	40	19	Loam	0.13
LVg	Gleyic Luvisols	80	11	9	Silty Loam	0.26
LPk	Rendzic Leptosols	37	44	19	Loam	0.13
CMc2	Calcaric Cambisol	76	12	12	Sandy Loam	0.43
LVk	Calcic Luvisols	53	24	23	Sandy Clay Loam	0.06
CMe	Eutric Cambisols	23	29	48	Clay	0.01
RGc	Calcaric Regosols	44	35	21	Loam	0.13

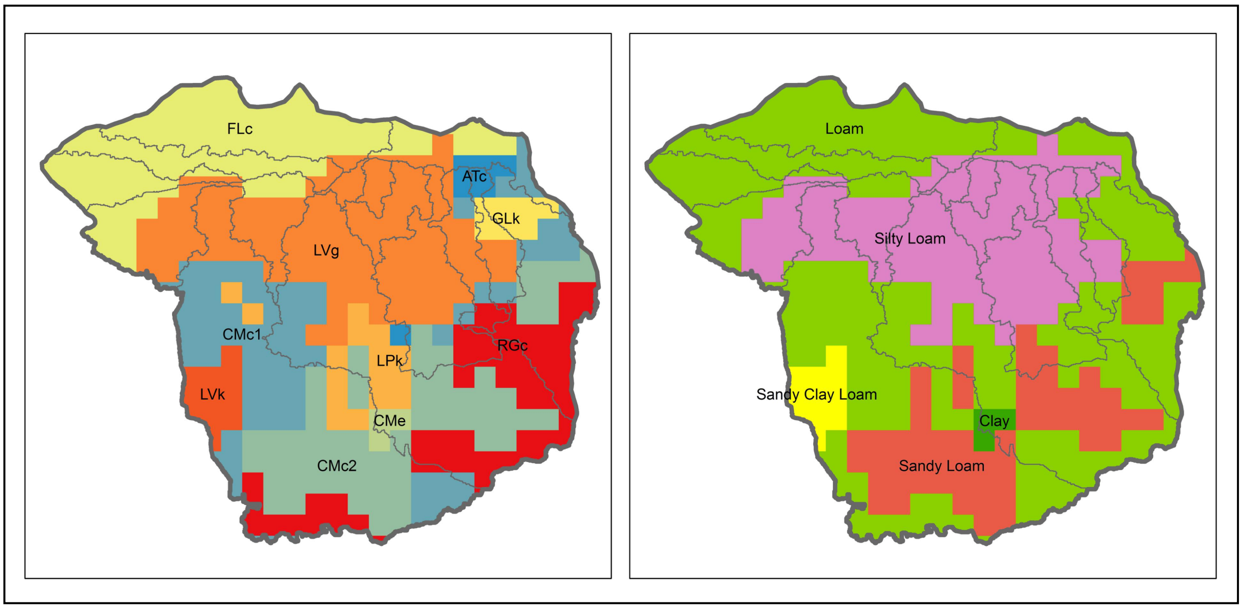


Figure 5-7: Soil spatial distribution in the study area

Other parameters of the subcatchment element were estimated based on observation records, recommended formulas or models by SWMM User Manual. The final parameters values of 15 subcatchments are shown in Table 5-3.

Table 5-3: Parameters and their values of 15 subcatchments

No.	A_s [ac]	W [ft]	S [%]	$Impv$ [%]	$n\text{-}Impv$	$n\text{-}Pv$	$d_s\text{-}Impv$ [in]	$d_s\text{-}Pv$ [in]	f_0 [in/hr]	f_∞ [in/hr]
S1	4884.28	8751.76	8.31	25.93	0.012	0.17	0.1	0.35	3	0.20
S2	27083.85	20608.69	14.12	23.44	0.012	0.40	0.1	0.35	3	0.23
S3	3237.54	7125.30	7.23	13.39	0.012	0.17	0.1	0.35	3	0.14
S4	3219.84	7105.79	9.67	45.46	0.012	0.17	0.1	0.35	3	0.22
S5	20283.33	17834.66	20.07	37.38	0.012	0.40	0.1	0.35	6	0.20
S6	3575.41	7487.87	7.87	31.82	0.012	0.17	0.1	0.35	3	0.14
S7	593.07	3049.63	11.07	58.90	0.012	0.17	0.1	0.35	3	0.26
S8	8271.84	11389.28	7.71	33.71	0.012	0.17	0.1	0.35	3	0.13
S9	796.63	3534.46	12.37	56.82	0.012	0.17	0.1	0.35	3	0.26
S10	2387.36	6118.63	11.90	74.19	0.012	0.17	0.1	0.35	3	0.26
S11	6921.41	10418.19	17.02	53.05	0.012	0.40	0.1	0.35	6	0.26
S12	2887.07	6728.59	13.07	57.28	0.012	0.40	0.1	0.35	3	0.21
S13	2087.08	5720.91	12.27	59.84	0.012	0.40	0.1	0.35	3	0.21
S14	8179.99	11325.87	19.77	41.90	0.012	0.40	0.1	0.35	6	0.21
S15	3794.14	7713.51	9.17	65.39	0.012	0.17	0.1	0.35	3	0.17

The values of shape parameters of the junction element and conduit element were calculated by the geometry statistics module of ArcGIS. Invert elevation, maximum water depth, and initial water depth were calculated from observations. SWMM is generally applied to the design of urban drainage system with regular pipes, mostly circular. However, it can also support other cross-sectional shapes of the river or channel, such as rectangular and trapezoidal. In this study, the reach was represented by the conduit element. The cross-section of the natural reach generally has various shapes in different parts. According to field survey and the cross-section drawing of major reaches, the cross-section of main river in the study area is approximate to a rectangular, so the corresponding parameters only refer to the river bottom width. Parameters values of the junctions and conduits are shown in Table 5-4 and Table 5-5.

Table 5-4: Parameters and their values of junctions

No.	Z [ft]	Max.Depth [ft]	Initial. Depth [ft]
J1	71.33	18.41	7.50
J2	70.81	17.59	6.32
J3	61.15	17.59	13.48
J4	60.25	16.70	11.21
J5	59.09	16.70	10.33
J6	58.43	18.47	10.50
J7	57.80	18.47	10.96
J8	56.71	18.86	11.80
J9	56.24	18.86	12.20
J10	55.89	18.86	12.51
J11	55.61	18.86	12.76
J12	54.79	20.47	13.36
O1	54.66	-	-

Table 5-5: Parameters and their values of conduits

ID	Shape	Length[ft]	Max.Depth [ft]	*n*	Bottom Width[ft]
C1	rectangular	2838.47	17.59	0.03	164.04
C2	rectangular	11944.56	17.59	0.03	164.04
C3	rectangular	4768.94	16.70	0.03	196.85
C4	rectangular	6376.44	16.70	0.03	196.85
C5	rectangular	1346.72	18.47	0.03	229.66
C6	rectangular	3421.17	18.47	0.03	229.66
C7	rectangular	6029.26	18.47	0.03	229.66
C8	rectangular	3968.97	18.86	0.03	229.66
C9	rectangular	2958.60	18.86	0.03	229.66
C10	rectangular	2408.28	18.86	0.03	229.66
C11	rectangular	6993.91	20.47	0.03	262.46
C12	rectangular	1081.48	20.47	0.03	262.46

Since the research objective is to compare the efficiency of combined LIDs, in the case of ensuring that the values of parameters of the three individual LID practice of scenarios are the same, no detailed LIDs design considering local characteristics was involved. All LIDs adopted the standard parameters values provided by the Sponge City Handbook and SWMM User Manual. Parameters and their values of individual LID practice are shown in Table 5-6, 5-7, and 5-8.

Table 5-6: Parameters and their values of the Permeable Pavement

Permeable Pavement（permeable concrete）			**Standards**	
Surface	Berm Height [in]	5.91	CJJ37-2012	≥150mm
	Vegetative Volume Fraction	0	Recommendation by SWMM User's Manual	Ignored
	Surface Roughness	0.012	Recommendation by SWMM User's Manual	Concrete
	Surface Slope *(percent)*	2.00	CJJ/T135-2009	1%~2%
Pavement	Thickness [in]	7.09	CJJ/T135-2009	≥180mm
	Void Ratio	0.10	CJJ/T135-2009	≥10%
	Impervious Surface Fraction	0	Recommendation by SWMM User's Manual	Continuous porous pavement
	Permeability [in/hr]	70.87	CJJ/T135-2009	≥0.5mm/s
	Clogging Factor	0	Recommendation by SWMM User's Manual	Ignored
Storage	Thickness [in]	5.91	CJJ/T135-2009	≥150mm
	Void Ratio	0.5	Recommendation by SWMM User's Manual	0.5~0.75
	Seepage Rate [in/hr]	0.21	FAO/ Recommendation by SWMM User's Manual	Average minimum soil infiltration rate
	Clogging Factor	0	Recommendation by SWMM User's Manual	Ignored

Table 5-7: Parameters and their values of the Rain Garden

Rain Garden			Standards	
Surface	Berm Height [in]	11.81	Sponge City Handbook	200~300mm
	Vegetative Volume Fraction	0	Recommendation by SWMM User's Manual	Ignored
	Surface Roughness	0	Recommendation by SWMM User's Manual	Only for roof surface, pavement surface or vegetative swale
	Surface Slope *(percent)*	0	Recommendation by SWMM User's Manual	Only for roof surface, pavement surface or vegetative swale
Soil	Thickness [in]	9.84	Sponge City Handbook	250~1200mm
	Porosity *(fraction)*	0.46	FAO/ Recommendation by SWMM User's Manual	Soil: Loam
	Field Capacity	0.23	FAO/ Recommendation by SWMM User's Manual	Soil: Loam
	Wilting Point	0.12	FAO/ Recommendation by SWMM User's Manual	Soil: Loam
	Conductivity [in/hr]	0.13	FAO/ Recommendation by SWMM User's Manual	Soil: Loam
	Conductivity Slope	30	Recommendation by SWMM User's Manual	30~60
	Suction Head [in]	3.5	FAO/ Recommendation by SWMM User's Manual	Soil: Loam

Table 5-8: Parameters and their values of the Rain Barrel

Rain Barrel			Standards	
Storage	Barrel height [in]	36	Recommendation by SWMM User's Manual	600~900mm
	Flow coefficient [in/hr]	1	Recommendation by SWMM User's Manual	-
	Flow exponent	0.5	Recommendation by SWMM User's Manual	-
	Offset Height [in]	10	Recommendation by SWMM User's Manual	-
Drain	Drain Delay *(hours)*	6	Recommendation by SWMM User's Manual	-

5.1.4 Verification

In general, for forecasting and designing simulation, sufficient observation is required to calibrate and verify the model and ensure simulation accuracy. In this study, the daily average runoff records from 2006 to 2011 were used to verify the model. According to the SWMM User Manual, this is sufficient for long-term comparative simulation in a large spatial scale area, because the variation of the basic scenario is consistent, and the relative effect is not significant. Figure 5-8 shows the curve of measured and simulated values. As shown in the figure, the initial values of the measured records are all slightly higher than the simulated values. This might because the measured values include not only surface runoff but also base flow. The base flow refers to the stable flow from the recharge of the groundwater. The simulated values are much higher than the measured value, on the one hand because the model assumes that subcatchment runoff is directly discharged into the junction, while the actual subcatchment runoff would preferentially run into its own tributaries to be stored or recharge the groundwater; on the other hand, to the model parameters, since SWMM requires the time step of the precipitation or rainfall less than 1 hour for the long-term simulation, but the measured data of the precipitation in the study area is the daily scale, after the rough discrete hourly precipitation was brought into the model. Due to the large area of the study, some parameters used the average values, such as average slope and infiltration rate. The finer the discreteness of the spatial scale, the more accurate the relevant values of parameters would be, but at the same time the time cost and complexity also would raise. By calculating the R^2 of the measured and simulated values, the result is more than 0.5 which is acceptable for comparison simulation. In addition, the variation trend of the measured values is same as the simulated values', and the occurrence of runoff peak remains same as well.

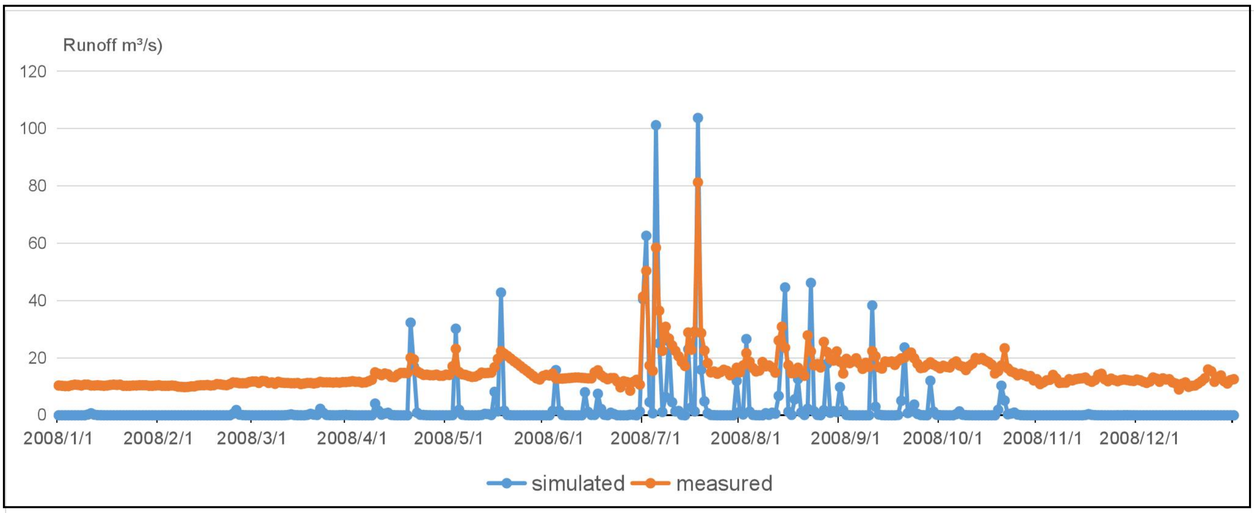


Figure 5-8: The fitted curve of measured runoff and simulated runoff (in 2008)

5.2 Effectiveness comparison and analysis of LIDs

5.2.1 Urbanization effect on runoff

The corresponding imperviousness values were estimated based on the land use of the study area in 1979, 1989, 1999, 2009 and 2017, then brought into the model to simulate the change in runoff volume and peak runoff in the watershed and subcatchments, and to compare and analyze the effect of urbanization on runoff. The runoff volume of subcatchments and the whole watershed expressed by total inflow of the outfall are shown in Table 5-9.

Table 5-9: Runoff volume of the subcatchments and the whole watershed [unit: 10^6 gal]

No.	1979	1989	1999	2009	2017
S1	1816.86	3634.22	4055.24	4936.31	6050.33
S2	6663.67	10929.96	17061.33	24903.05	35397.17
S3	1343.81	1764.48	1885.19	2077.10	2190.72
S4	814.82	2509.89	4258.44	5390.18	7154.39
S5	15410.19	20969.34	25488.93	29758.98	31885.98
S6	1781.52	2496.24	3103.26	4554.51	4789.84
S7	1023.74	1237.22	1287.62	1288.84	1291.21
S8	3984.18	5807.47	7288.18	10892.26	13671.31
S9	1593.02	1627.73	1669.24	1669.24	1667.82
S10	5086.38	6342.07	6397.92	6397.54	6372.08
S11	8293.31	11427.18	12210.24	12909.56	13021.93
S12	3528.44	5283.69	5857.24	5917.89	5928.50
S13	3165.02	4277.61	4408.38	4474.5	4489.58
S14	4726.05	7356.74	10216.65	12240.23	12866.25
S15	4999.04	6810.62	8474.48	8937.21	8796.22
O1	65986.71	94584.40	116017.50	138918.79	158203.80

As can be seen from Table 5-9, the runoff volume in the whole watershed increased in turn, which is consistent with the change in urbanization rate (Figure 5-9). Due to the various area and precipitation of each subcatchment, in order to eliminate the influence of uneven distribution of area and precipitation, the runoff coefficient was used to compare the change of runoff in each subcatchment. The runoff coefficient was calculated by dividing the runoff volume by the total precipitation, and can reflect the capacity of some area of generating runoff. Its value is generally between 0 and 1. The larger the value is, the stronger the runoff generation capacity of the area, and vice versa. The runoff coefficient of each subcatchment is shown in Table 5-10 and Figure 5-10.

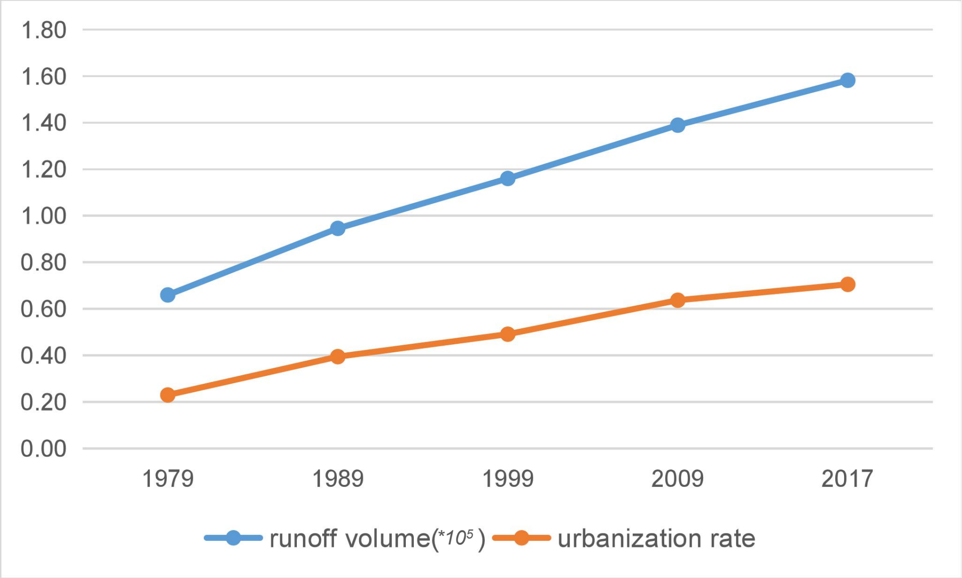


Figure 5-9: The change curve of runoff volume and urban rate

Table 5-10: Runoff coefficients of the subcatchments

No.	1979	1989	1999	2009	2017
S1	0.084	0.168	0.187	0.228	0.279
S2	0.052	0.086	0.134	0.195	0.277
S3	0.093	0.123	0.131	0.144	0.152
S4	0.057	0.176	0.299	0.378	0.502
S5	0.159	0.216	0.263	0.307	0.329
S6	0.113	0.158	0.196	0.288	0.303
S7	0.390	0.472	0.491	0.491	0.492
S8	0.109	0.159	0.199	0.298	0.374
S9	0.452	0.462	0.474	0.474	0.473
S10	0.482	0.601	0.606	0.606	0.603
S11	0.273	0.376	0.402	0.425	0.428
S12	0.278	0.417	0.462	0.467	0.467
S13	0.345	0.466	0.481	0.488	0.49
S14	0.132	0.205	0.284	0.341	0.358
S15	0.296	0.403	0.502	0.529	0.521

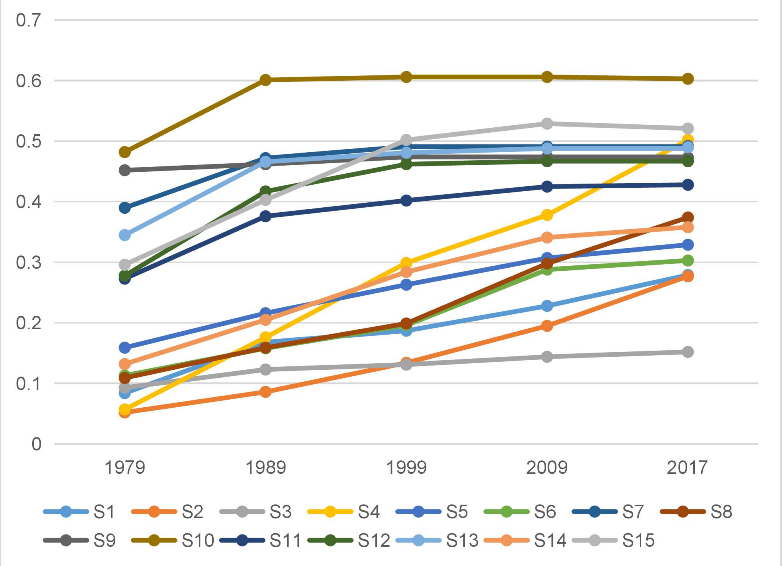
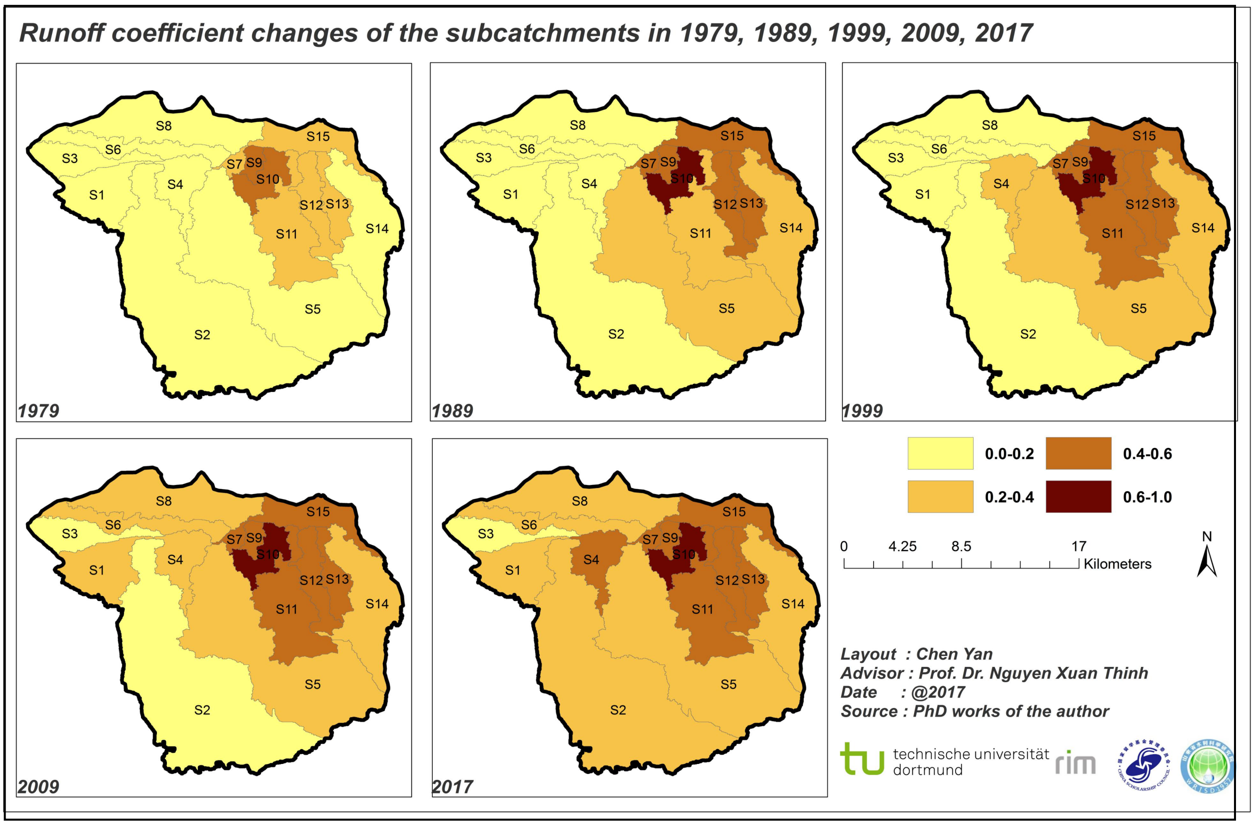


Figure 5-10: The change curve of runoff coefficients

As shown, with the urban development of Jinan city, the impervious area has increased, and the runoff capacity of each subcatchment has gradually increased, and the increasing trend is different due to different levels of regional development, such as economic factors and policy factors. The runoff coefficients of subcatchment S1, S2, S3, S4, S5, S6, S8, and S14 continues to increase from 1979 to 2017. The increase trend of S3 is not significant, indicating that the urban development level in the region might be lower, while the growth rate of runoff coefficient in S4 from 2009 to 2017 is the largest, indicating that during this period, the urban development intensity in the region might be greater, and the urban construction was faster; the runoff coefficients of S7, S9, S10, S11, S12, S13, and S15 show growth in initial stages and keep a steady state in the latter years, indicating that the initial urbanization levels in these areas are relatively high due to located in the urban center area; on the other hand, it indicates that the construction of urban areas in the areas since 1989 has been relatively completely. It is worth noting that the runoff coefficients of S9, S10, and S15 decreased from 2009 to 2017. After investigation, it is found that the flooding and waterlogging in the those parts and their adjacent areas are relatively seriously. The investigation by the local government department find that there are many illegal construction and sheds over some rivers, resulting in a reduction in drainage capacity of the river. During 2015, the government dismantled illegal sheds. In addition, with the advancement of the sustainable development, the increase in the greening area or the installation of some runoff regulation measures might also reduce the generation of runoff. Figure 5-11 shows the spatial variation of runoff coefficients of the subcatchments in 1979, 1989, 1999, 2009, and 2017. As can be seen from the figure, the spatial variation trend of runoff coefficient presents a ”Z-shape” of “South-North-South”. This could also indirectly reflect the direction of urban development and construction in the study area over the past three decades.


Runoff coefficient changes of the subcatchments in 1979, 1989, 1999, 2009, 2017

Layout : Chen Yan
Advisor : Prof. Dr. Nguyen Xuan Thinh
Date : @2017
Source : PhD works of the author

Figure 5-11: Runoff coefficient changes of the subcatchments in different periods

According to the simulation results, the peak runoff of the whole watershed and subcatchments is shown in Table 5-11. The trend of peak runoff in the subcatchment varies similarly with the trend of runoff volume and urbanization rate. It proves the effect of urbanization on runoff volume and peak runoff at the same time, and provides a reference for urban development of Jinan city. In addition, the results served as a basis of the layout of LIDs.

Table 5-11: Peak runoff of the subcatchments [unit: ft^3/s]

No.	1979	1989	1999	2009	2017
S1	938.43	1135.47	1180.64	1274.34	1390.93
S2	2230.11	2781.80	3579.23	4603.57	5978.02
S3	835.00	874.19	885.36	903.04	913.46
S4	384.82	592.29	815.81	977.65	1224.79
S5	4650.83	5511.08	6212.17	6873.71	7202.41
S6	677.45	761.54	833.07	1003.50	1030.94
S7	194.09	221.77	228.15	228.31	228.60
S8	1291.24	1520.44	1708.61	2170.54	2541.89
S9	286.44	290.97	296.36	296.36	296.18
S10	857.34	1029.57	1036.95	1036.90	1033.54
S11	1811.36	2324.51	2452.15	2565.76	2583.98
S12	943.65	1195.42	1273.63	1281.73	1283.15
S13	788.80	937.73	954.29	962.57	964.46
S14	1459.38	1884.67	2347.66	2674.20	2774.82
S15	1286.29	1411.42	1519.82	1552.84	1542.92
O1	12673.92	15905.52	18437.45	21094.61	21268.42

5.2.2 Effectiveness of LIDs in the large spatial scale watershed

Based on the results of section 5.2.1 and the land use of the study area in 2017, LIDs were deployed in the subcatchments whose runoff coefficient are greater than value 0.4, as shown in Figure 5-12. The LIDs element was created in SWMM, inputting parameters to simulate the changes of peak runoff and runoff volume in the watershed and subcatchments under the three combined LIDs scenarios.

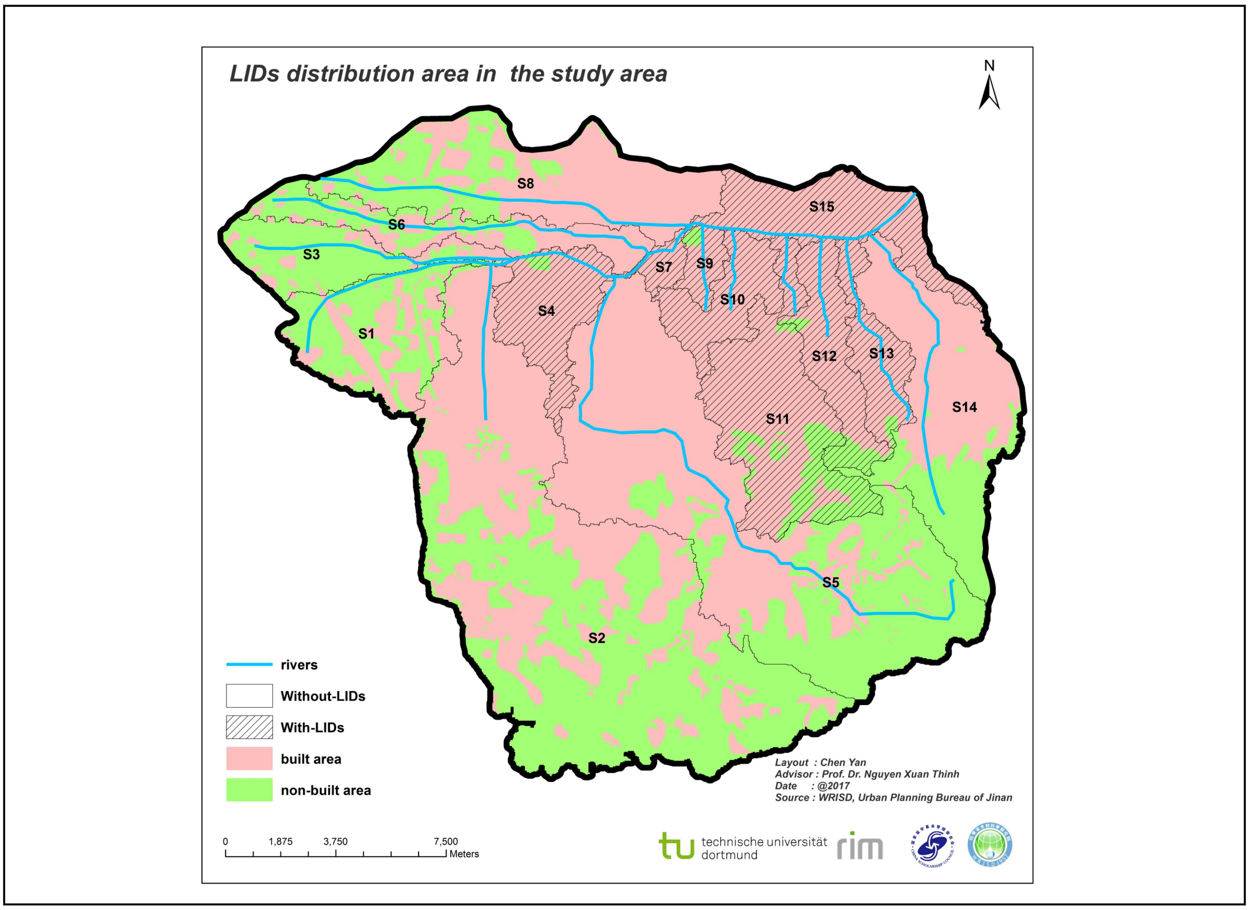


Figure 5-12: LIDs distribution of the study area

Table 5-12 and 5-13 respectively show the changes in runoff volume and peak runoff in the subcatchments and outfall of the watershed before and after the deployment of LIDs. As can be seen from the tables, whether in the subcatchments or in the whole watershed, the reduction of runoff volume in the three scenarios is much greater than the reduction in peak runoff. On the one hand, due to the capacity of the three individual LID practice on regulating runoff volume is superior than on peak runoff, so the combination shows the equivalent performance; on the other hand, it also shows that the three individual LID practice has better regulating effect on the small runoff than the large runoff. Therefore, although the runoff volume decreased, the peak

Runoff reduction is not obviously. The reduction rate in runoff volume and peak runoff in each subcatchment is greater than in the whole watershed. Firstly, this might because some subcatchments within the watershed didn't deploy LIDs, the integrated effect on the entire study area is less than that of all individual subcatchment with LIDs. It might also due to the possibility that the effect of LIDs on runoff gradually diminished with increasing spatial scale. Comparing the reduction of the total amount of runoff and the peak runoff of the three scenarios, it is found that the control effect of scenario 1 is better for runoff volume, and scenario 2 and scenario 3 are degressive; Scenario 2 has a better control effect for peak runoff, while both scenario 1 and scenario 3 are in descending order.

Table 5-12: Runoff volume changes before and after LIDs [unit: 10^6 gal]

No.	Base	Scenario 1	Scenario 2	Scenario 3	Scenario 1 Reduction%	Scenario 2 Reduction	Scenario 3 Reduction%
S4	7154.39	2607.89	3169.52	4234.35	63.55	55.70	40.81
S7	1291.21	466.62	551.47	753.90	63.86	57.29	41.61
S9	1667.82	577.05	735.62	972.46	65.40	55.89	41.69
S10	6372.08	2653.48	2771.96	3844.14	58.36	56.50	39.67
S11	13021.93	3217.96	4917.60	7019.75	75.29	62.24	46.09
S12	5928.50	1816.48	2434.71	3361.68	69.36	58.93	43.30
S13	4489.58	1395.91	1986.76	2584.74	68.91	55.75	42.43
S15	8796.22	3330.46	3969.57	5272.13	62.14	54.87	40.06
O1	158203.80	125816.21	130352.97	137838.00	20.47	17.60	12.87

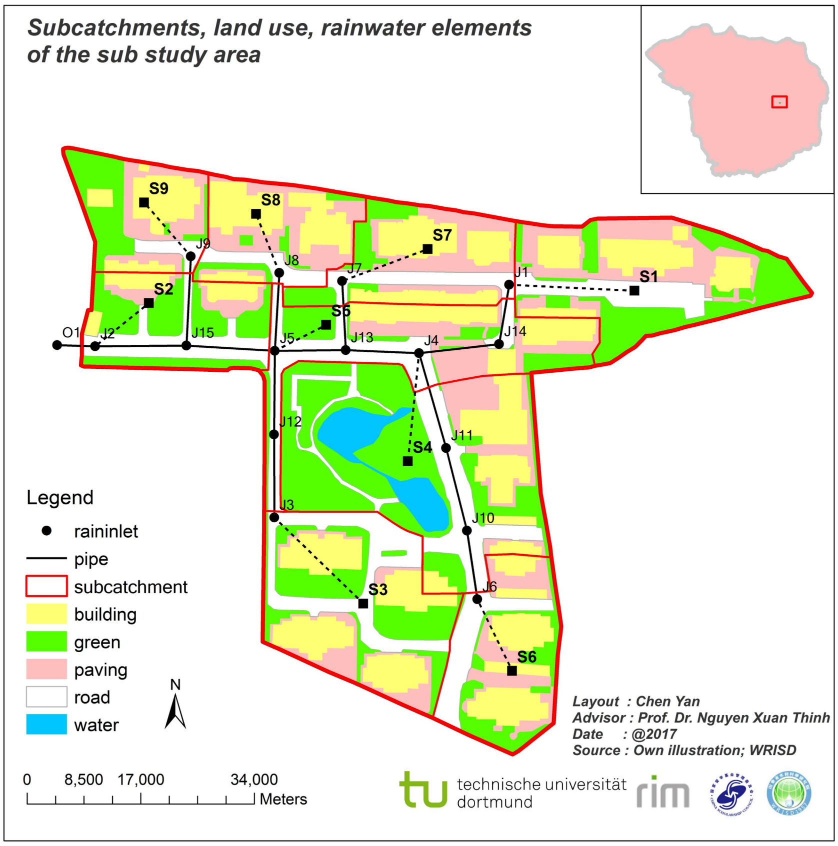
Table 5-13: Peak runoff changes before and after LIDs [unit: ft^3/s]

No.	Base	Scenario 1	Scenario 2	Scenario 3	Scenario 1 Reduction%	Scenario 2 Reduction	Scenario 3 Reduction%
S4	1224.79	1083.31	921.73	1093.90	11.55	24.74	10.69
S7	228.60	211.39	181.84	214.20	7.53	20.45	6.30
S9	296.18	277.87	243.37	281.65	6.18	17.83	4.91
S10	1033.54	909.08	763.13	934.08	12.04	26.16	9.62
S11	2583.98	2203.96	1877.65	2287.99	14.71	27.33	11.45
S12	1283.15	1153.54	998.42	1172.49	10.10	22.19	8.62
S13	964.46	893.26	793.27	903.18	7.38	17.75	6.35
S15	1542.92	1399.12	1227.74	1410.18	9.32	20.43	8.60
O1	21268.42	21146.60	20956.50	21154.44	0.57	1.47	0.54

Since the deployment of LIDs in each subcatchment was mainly determined by the impervious area ratio, while the impervious surface in each subcatchment, such as the proportion of roof and pavement, is different, leading to the difference of the area or number of LIDs of three scenarios. In order to eliminate the effect, the average cost for reducing per cubic meter runoff was calculated based on the construction and maintenance costs of individual LID practice and simulation results of three scenarios. For reducing per cubic meter runoff, scenario 1 will cost about 1.95 euros, scenario 2 will cost 4.47 euros and scenario 3 will cost about 3.53 euros. This result also indirectly proves that the capacity of the three individual LID practice, Rain Barrel, Rain Garden, and Permeable Pavement, for reducing runoff volume weakens in turn. It should be noted that the price of the three individual LID practice was mainly determined based on the cost in China, it might be different in other counties or regions.

5.2.3 LIDs in response to extreme storms

Based on the findings of the previous section, a residential area in subcatchment S11 was selected as a secondary study area to identify the response of the combined LIDs to extreme storms. The subcatchments in sub study area were created according to the flow direction of rain pipe and the location of rain inlet of the drainage system. The land use, main drainage pipes and rain inlets, and subcatchments of the sub study area are shown in Figure 5-13. Land use consists of building area, green area, road, paving area and pond. Nine subcatchments were divided from the sub study area. Each subcatchment contains multiple types of land use.


Subcatchments, land use, rainwater elements of the sub study area

Layout : Chen Yan
Advisor : Prof. Dr. Nguyen Xuan Thinh
Date : @2017
Source : Own illustration; WRISD

Figure 5-13: Subcatchments, land use and rainwater elements of the sub study area

On the basis of design storm formula of Jinan city and the Chicago model. Twelve design storms with different recurrence interval (or return period) and duration were produced, as shown in Figure 5-14. The recurrence interval is 1a, 3a, 10a and 100a respectively. The rainfall duration is 1h, 2h and 4h respectively. The time step is 5 minutes. As can be seen from the figure, the peak intensity of the design storm of same return period is same, and the excess rain is supplemented by the distribution of rainfall on both sides of the peak according to the duration. The rainfall intensity of different return period increases sequentially. The minimum value is 2.84 in/hr and the maximum is 13.44 in/hr.

Return period (a)	*1*	*3*	*10*	*100*	*1*	*3*	*10*	*100*	*1*	*3*	*10*	*100*
Time (min) \ Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12
5	0.78	1.07	1.38	1.97	0.41	0.56	0.73	1.04	0.25	0.34	0.44	0.63
10	1.07	1.45	1.87	2.68	0.47	0.63	0.82	1.17	0.26	0.36	0.46	0.66
15	1.75	2.38	3.07	4.39	0.53	0.73	0.94	1.34	0.28	0.38	0.49	0.70
20	5.35	7.28	9.39	13.44	0.63	0.86	1.11	1.59	0.30	0.41	0.52	0.75
25	2.84	3.87	4.99	7.15	0.78	1.07	1.38	1.97	0.32	0.43	0.56	0.80
30	1.93	2.63	3.39	4.85	1.07	1.45	1.87	2.68	0.34	0.47	0.60	0.87
35	1.47	2.00	2.58	3.70	1.75	2.38	3.07	4.39	0.38	0.51	0.66	0.94
40	1.20	1.63	2.10	3.00	5.35	7.28	9.39	13.44	0.41	0.56	0.73	1.04
45	1.01	1.38	1.78	2.55	2.84	3.87	4.99	7.15	0.47	0.63	0.82	1.17
50	0.88	1.20	1.55	2.22	1.93	2.63	3.39	4.85	0.53	0.73	0.94	1.34
55	0.78	1.07	1.38	1.97	1.47	2.00	2.58	3.70	0.63	0.86	1.11	1.59
60	0.71	0.97	1.24	1.78	1.20	1.63	2.10	3.00	0.78	1.07	1.38	1.97
65					1.01	1.38	1.78	2.55	1.07	1.45	1.87	2.68
70					0.88	1.20	1.55	2.22	1.75	2.38	3.07	4.39
75					0.78	1.07	1.38	1.97	5.35	7.28	9.39	13.44
80					0.71	0.97	1.24	1.78	2.84	3.87	4.99	7.15
85					0.65	0.88	1.14	1.63	1.93	2.63	3.39	4.85
90					0.60	0.81	1.05	1.50	1.47	2.00	2.58	3.70
95					0.56	0.76	0.98	1.40	1.20	1.63	2.10	3.00
100					0.52	0.71	0.92	1.31	1.01	1.38	1.78	2.55
105					0.49	0.67	0.86	1.24	0.88	1.20	1.55	2.22
110					0.47	0.63	0.82	1.17	0.78	1.07	1.38	1.97
115					0.44	0.60	0.77	1.11	0.71	0.97	1.24	1.78
120					0.42	0.57	0.74	1.06	0.65	0.88	1.14	1.63
125									0.60	0.81	1.05	1.50
130									0.56	0.76	0.98	1.40
135									0.52	0.71	0.92	1.31
140									0.49	0.67	0.86	1.24
145									0.47	0.63	0.82	1.17
150									0.44	0.60	0.77	1.11
155									0.42	0.57	0.74	1.06
160									0.40	0.55	0.71	1.01
165									0.39	0.52	0.68	0.97
170									0.37	0.51	0.65	0.93
175									0.36	0.49	0.63	0.90
180									0.34	0.47	0.60	0.87
185									0.33	0.45	0.59	0.84
190									0.32	0.44	0.57	0.81
195									0.31	0.43	0.55	0.79
200									0.30	0.41	0.53	0.76
205									0.30	0.40	0.52	0.74
210									0.29	0.39	0.50	0.72
215									0.28	0.38	0.49	0.70
220									0.27	0.37	0.48	0.69
225									0.27	0.36	0.47	0.67
230									0.26	0.35	0.46	0.65
235									0.26	0.34	0.45	0.64
240									0.25	0.34	0.44	0.63

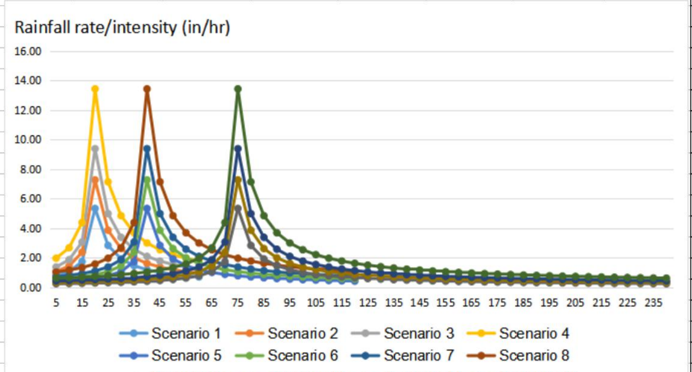


Figure 5-14: Scenarios of the design storms of the sub study area [unit: in/hr]

The runoff volume and the peak runoff of the outfall O1 are shown in Table 5-14 and Table 5-15. From the tables, it can be seen that the effect of the combined LIDs on peak runoff and runoff volume is significantly different under different return periods and duration. With the increase of return period, the effect of the combined LIDs on both peak runoff and runoff volume will decrease, and the reduction rate of runoff volume from 1a to 100a changes from 44.330% to 26.996%, for the peak runoff, it reduces from 54.899% to 30.237%, indicating that the combined LIDs have better control over medium and small intensity storms, and have less control over heavy storms; In addition, comparing the results of scenarios with same return period but different duration, it can be summarized that the control effect of the combined LIDs on runoff peak runoff and runoff volume has been weakened, but not obviously. For example, for the return period of 100a, with the increase in duration from 1 hour to 2 hours and 4 hours, the reduction rates of runoff volume and peak runoff are about 25%. This might be due to the fact that as the water storage of the combined LIDs reaches saturation, their effect diminishes as the duration increases. In this case, the reducing rates of the peak runoff and runoff volume are small over the 2-hour period and 4-hour duration, indicating that the control effect of the combined LIDs is no longer affected after 2 hours from the start of rainfall. Of course, this is mainly related to the local underlying conditions and the initial soil moisture content, and the other regions might show different results. In addition, the change curves of runoff before and after deploying LIDs are shown in Figure 5-15, Figure 5-16, Figure 5-17,Figure 5-18. As can be seen from the figures, regardless of storm with a small or large intensity, the occurrence time of runoff and peak are lagged.

Table 5-14: Runoff volume /total inflow of O1 before and after LIDs [unit: 10^6 gal]

Duration_return period	Without LIDs	With LIDs	Reduction%
60min_1a	0.194	0.108	44.330
60min_3a	0.292	0.185	36.644
60min_10a	0.400	0.269	32.750
60min_100a	0.589	0.430	26.995
120min_1a	0.268	0.163	39.179
120min_3a	0.398	0.263	33.920
120min_10a	0.539	0.373	30.798
120min_100a	0.785	0.580	26.115
240min_1a	0.352	0.222	36.932
240min_3a	0.518	0.349	32.625
240min_10a	0.696	0.489	29.741
240min_100a	1.014	0.753	25.740

Table 5-15: Peak runoff /maximum flow of O1 before and after LIDs [unit: ft³/s]

Duration_return period	Without LIDs	With LIDs	Reduction%
60min_1a	21.330	9.620	54.899
60min_3a	30.590	16.890	44.786
60min_10a	41.640	24.790	40.466
60min_100a	54.800	38.230	30.237
120min_1a	21.360	11.240	47.378
120min_3a	31.770	18.770	40.919
120min_10a	43.420	26.680	38.554
120min_100a	55.500	39.910	28.090
240min_1a	21.790	12.630	42.038
240min_3a	33.200	20.200	39.157
240min_10a	45.240	27.980	38.152
240min_100a	55.910	41.690	25.434

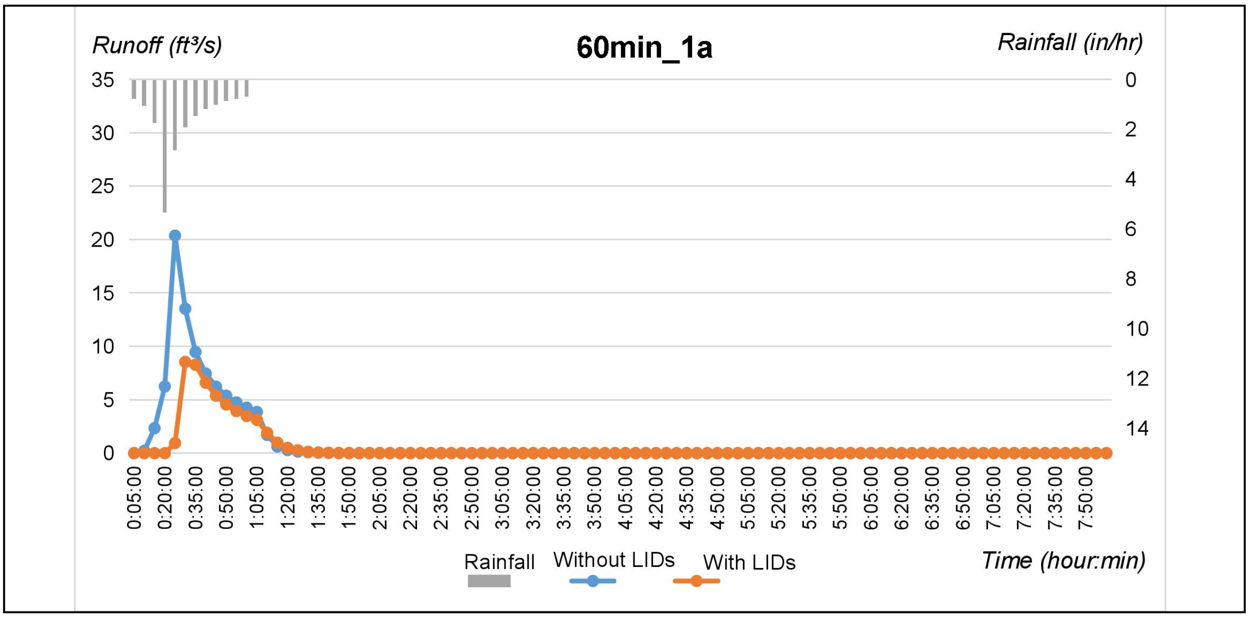


Figure 5-15: The change curve of runoff before and after LIDs (60min_1a)

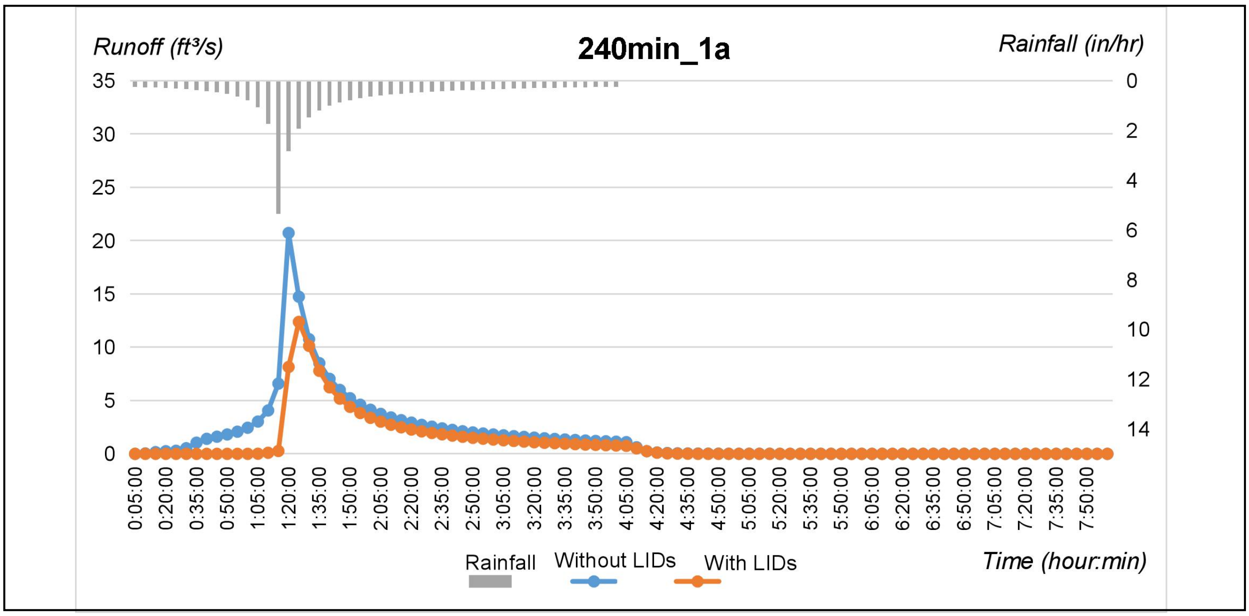


Figure 5-16: The change curve of runoff before and after LIDs (240min_1a)

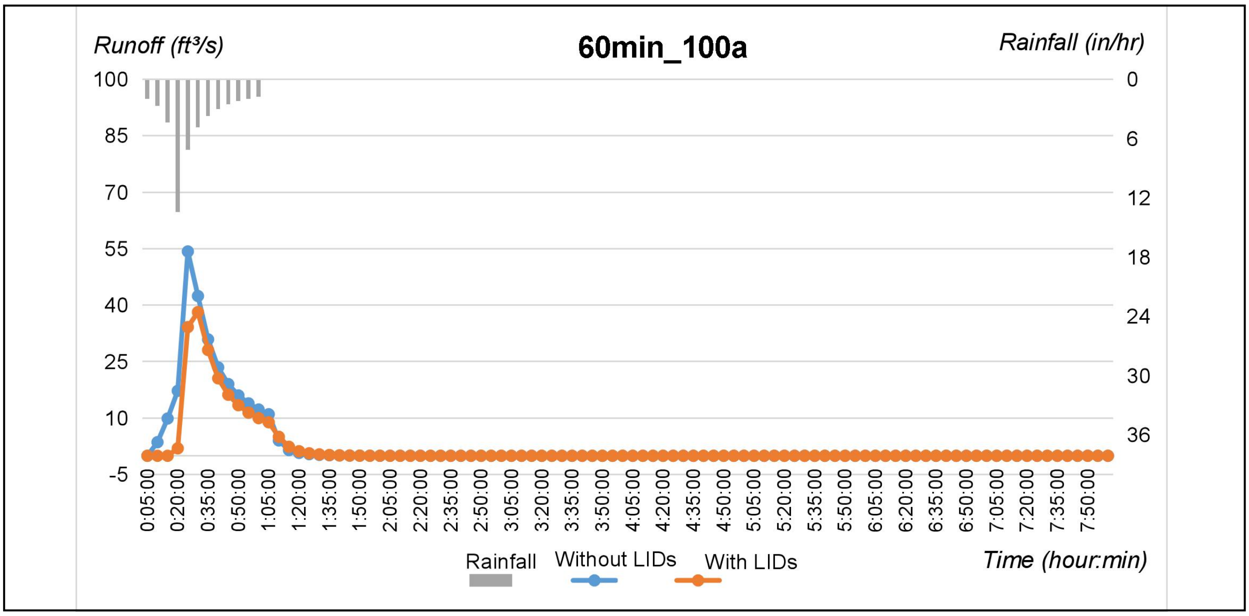


Figure 5-17: The change curve of runoff before and after LIDs (60min_100a)

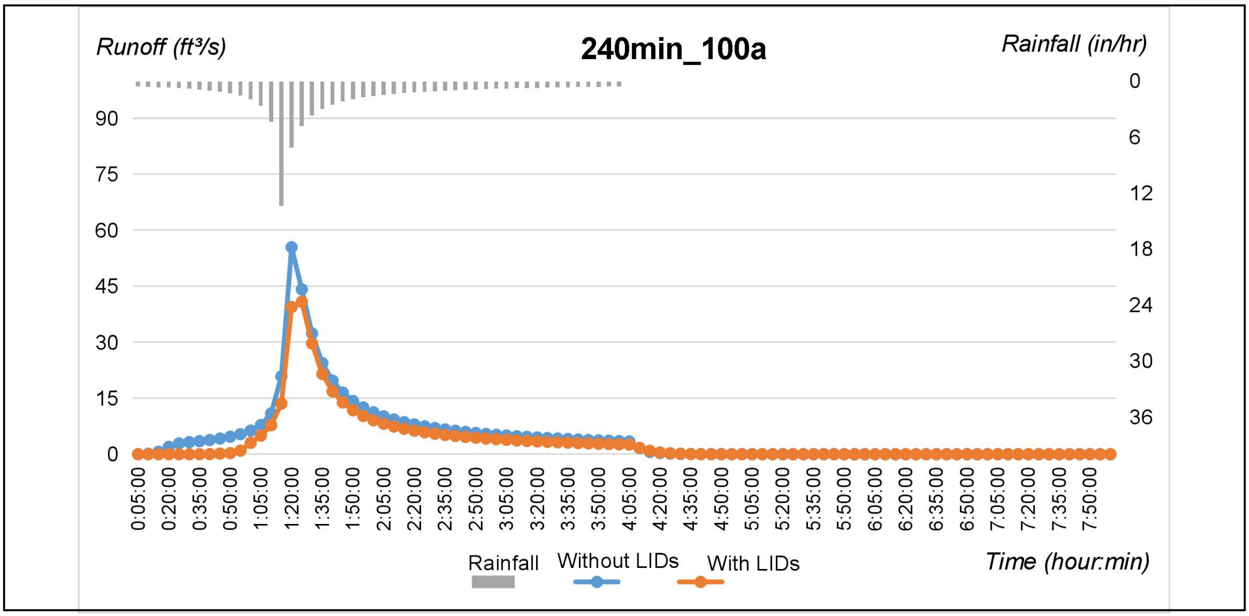


Figure 5-18: The change curve of runoff before and after LIDs (240min_100a)

5.3 Evaluation of LIDs based on the visualized scene

5.3.1 Inundated area estimation

In this study, inundated area refers to the area where rainwater overflow occurs when the amount of water in the receiving water body or water transmission carrier exceeds its storage capacity, then the water runs on the pavement. For example, overmuch rainwater from channels or drainage systems inundates farmlands or urban streets, or overflow from rain inlets or manholes when the drainage pipes are blocked, or due to heavy storm. When the runoff volume is too large exceeding the drainage capacity, flooding will occur. According to the SWMM simulation results, the storm with 10a return period and 1h duration caused overflow flooding in the junction J3 of the sub study area, and the storm of 100a return period leaded to the flooding of junction J3, J6, and J11; storms with more long duration and return period resulted in more overflow junctions. The overflow junctions and flooding volume are shown in Table 5-16.

Table 5-16: The overflow junctions and flooding volume [unit: 10^6 gal]

	Without LIDs						With LIDs					
	1h 10a	**1h 100a**	**2h 10a**	**2h 100a**	**4h 10a**	**4h 100a**	**1h 10a**	**1h 100a**	**2h 10a**	**2h 100a**	**4h 10a**	**4h 100a**
J1	0	0	0	0.001	0	0.001	0	0	0	0	0	0
J3	0.002	0.013	0.002	0.014	0.003	0.016	0	0.002	0	0.004	0	0.004
J4	0	0	0	0.001	0	0.002	0	0	0	0	0	0
J6	0	0.005	0	0.005	0	0.006	0	0	0	0	0	0
J11	0	0.005	0	0.007	0	0.009	0	0	0	0	0	0

The table also shows the change in the flooding volume of the overflow junctions after the combined LIDs were deployed. As can be seen from the table, for the return period of 10a which lasts for 1 hour, 2 hours, and 4 hours of storms, the flooding volume of overflow junctions was controlled better. After using the LIDs, no extra overflow was generated. For storms with the return period of 100a, the number of overflow junctions was reduced. The storm with the return period of 100a and duration of 4 hours was selected as the analysis of the inundation area. The unit gallon was converted to cubic meter, as shown in Table 5-17.

Table 5-17: The flooding volume in junctions after unit conversion

	Without LIDs		With LIDs	
	4h_100a [10^6 gal]	**4h_100a [m^3]**	**4h_100a [10^6 gal]**	**4h_100a [m^3]**
J1	0.001	3.7854	0	0
J3	0.016	60.5664	0.004	15.1416
J4	0.002	7.5708	0	0
J6	0.006	22.7124	0	0
J11	0.009	34.0686	0	0

The flooding flow curve in the overflow junction by SWMM could be used as the initial condition of the shallow water equation.Theoretically, the inundation simulation of 2D flooding can be performed based on the shallow water equation using the finite difference method. The flow velocity of each grid can be accurately simulated. That is, dynamic flooding process can be performed to determine the inundated area. However, due to the limitation of boundary conditions, complicated calculation, long time consuming, it is difficult to be executed effectively. In this study, seed algorithm was used to determine inundated area. Based on the simulation results of the storm runoff with return period of 100a and duration of 4h, DEM and flooding volume balance, the amount of filled water of eight grids of DEM adjacent to the overflow junction were calculated (taking the completion of seed filling as a basic time step). The symbolization method in ArcGIS was used to render the inundated area based the flooding depth of each grid. Before this, modules in ArcGIS, such as Raster to Point, Buffer Analysis and Feature Envelope To Polygon, were used to convert the raster DEM to shapefile data, to extract the grid where the road is located for inundated area analysis. Figure 5-18 shows the results of inundated area and flooding depth of J1 after two steps of seed calculation, J3 after 47 steps of seed calculation, J4 after one step of seed calculation, J6 after 3 steps of seed calculation, J11 after 8 steps of seed calculation. Among them, the steps of seed calculation of J1, J4, J6, and J11 are less due to less flooding volume from the overflow junctions and the large elevation difference between the seed point and filled grids. Because J3 has larger overflow flooding volume, the surrounding area is relatively flat, and the grid height difference is relatively small, at the same time, J3 has more pond areas, resulting in a large number of calculating. The inundated process occurred in the main east and west roads. When LIDs used, overflow occurred only at J3. The results are shown in Figure 5-19 as well. Both inundated area and flooding depth are decreased. At the same time, the figure can make the users more intuitively understand the scope of the flooding.

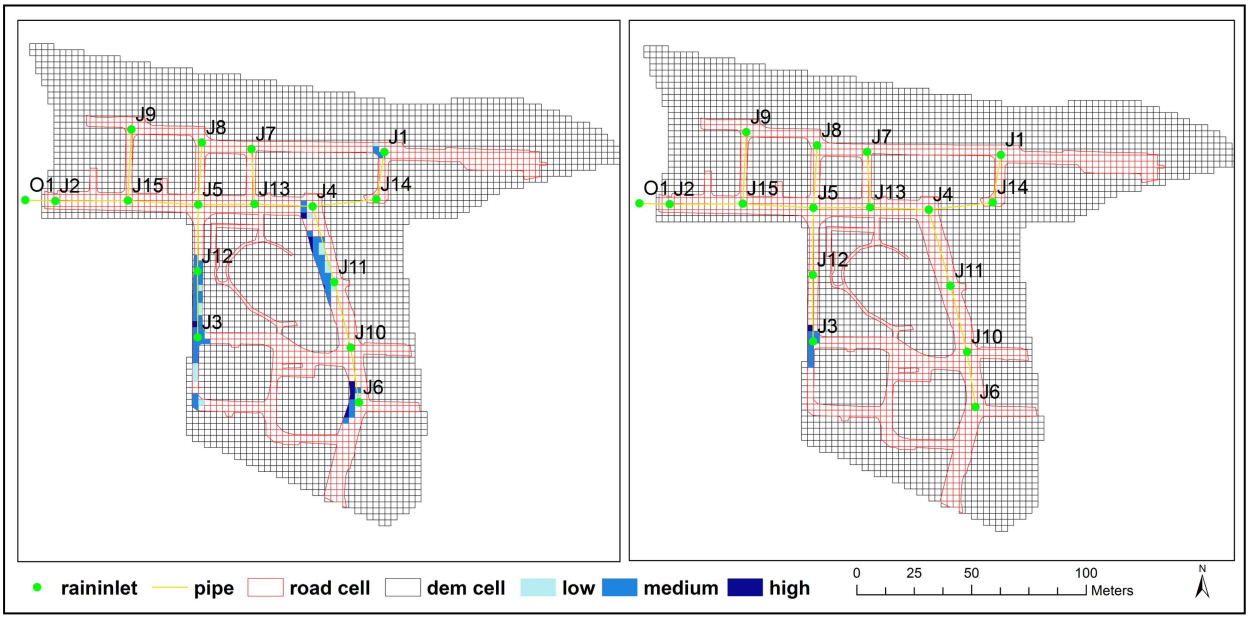


Figure 5-19: Inundated area change before and after LIDs

5.3.2 3D scene and "dynamic" flooding

As shown in Figure 5-20, in ArcScene, according to the attribute of the basic GIS data, the main element in the sub study area were extruded by setting the base height and extrusion value, and the 3D scene of this area was quickly established. Although the 3D effect could be well demonstrated, it can’t reflect the real in the study area yet. The 3D scene was exported from ArcScene to SketchUp via a plug-in to perform surface texture operation, and the buildings and roads were handled. The result is shown in Figure 5-21. By creating point features in ArcMap, the 3D model library of ArcScene was used to transform point features into decorative models such as vehicles and trees.

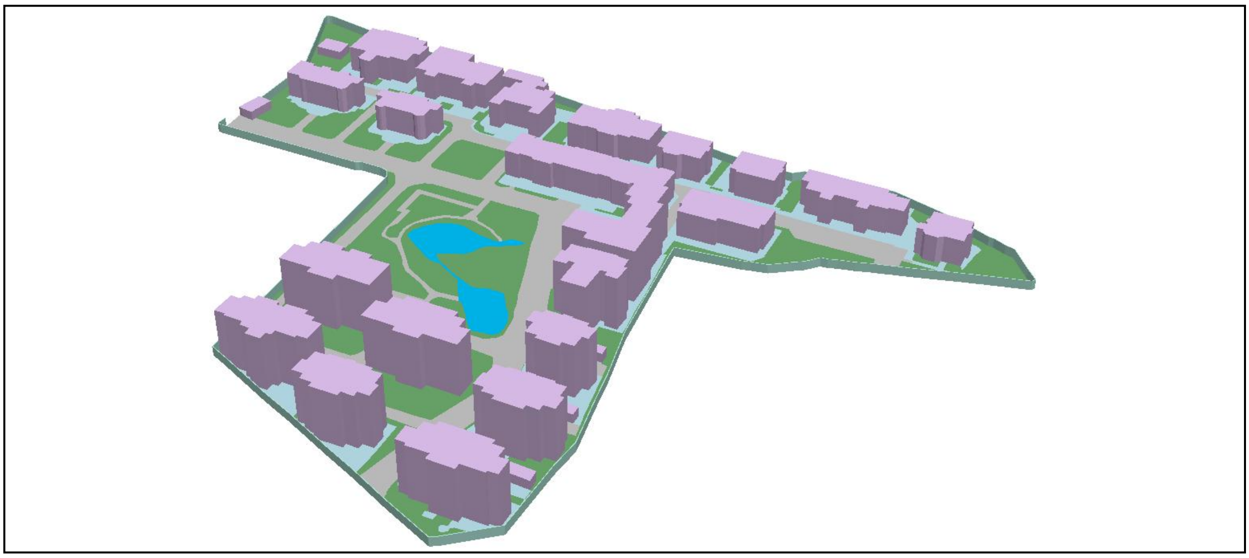


Figure 5-20: 3D effect of the sub study area in ArcScene

Figure 5-21: 3D scene of the sub study after texture operation

The generalization of the inundated area produced in 5.3.1 was performed. In the case that the basic range is not much different, each inundated area was converted into a smooth arc-shaped area according to the seed algorithm time step. Importing the processed inundated area into ArcScene and creating 3D elements in the same way by setting base height and extrusion. At last, using the animation module of ArcScene, based on the frame processing method to make each grid area form non-interrupted connection animation, presenting a "dynamic" flooding process, as shown in Figure 5-22.

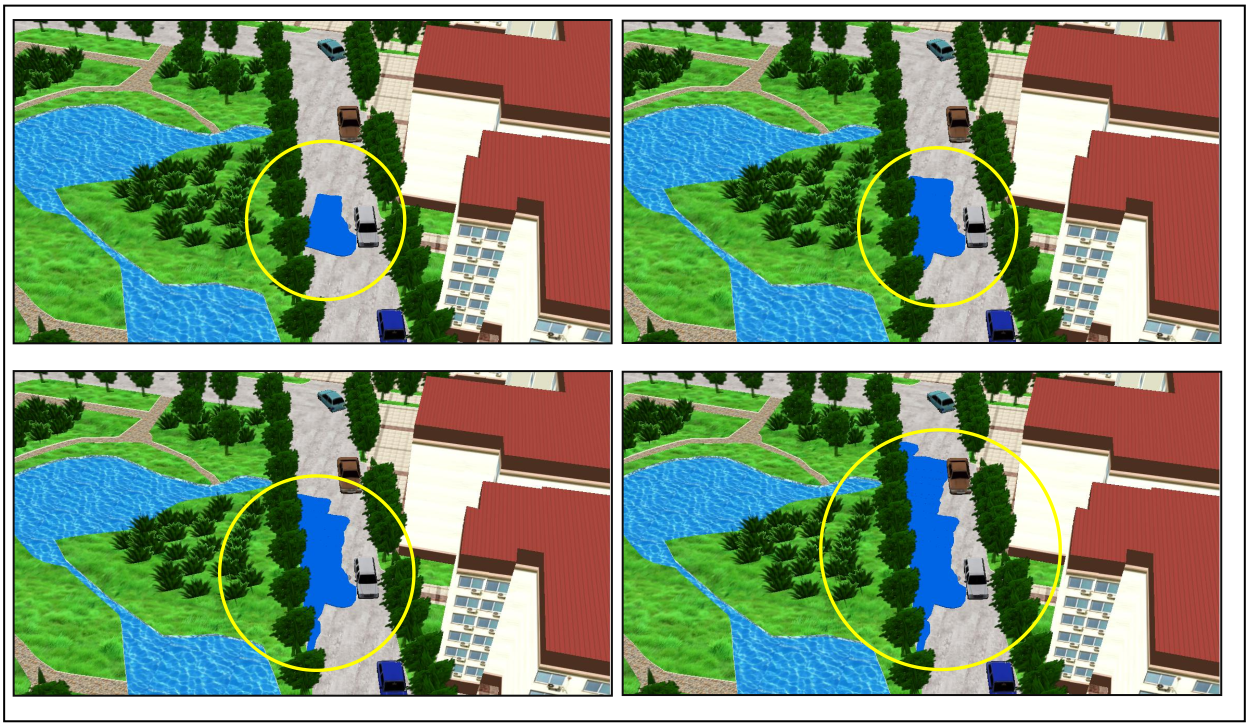


Figure 5-22: The "dynamic" flooding process (J11)

6. Discussion and conclusion

6.1 Implications

Urbanization has a significant impact on natural hydrological cycle through changing underlying surface and related artificial drainage and storage facilities construction. Therefore, it is necessary to implement appropriate urban planning and land development strategies in order to mitigate the negative impact of urbanization on runoff. As a typical representation, LIDs have been widely applied in developed counties. However, the existing studies engaging in the tasks of estimating the effectiveness of combined LIDs are limited. Focused on the gap, this study aimed to investigate an integrated idea to estimate the effectiveness of combined LIDs at expanded spatial scale and to explore the impact of urbanization on runoff using RS, GIS and hydrological modeling.

This study has made efforts to understand the effect of urbanization on runoff. In this study, the built-up area of the study area was extracted using RS method based on Landsat images. In addition, subcatchments and parameters of hydrological model were extracted and estimated by using GIS and mathematical models. The effectiveness of combined LIDs at watershed scale with different land use types was estimated by using the hydrological model, SWMM. In the meantime, the effectiveness of LIDs in response to extreme storms was also analyzed. In order to to increase public awareness and understanding of the LIDs benefits and to make planners and the public quickly summarize information about the impact of LIDs on runoff of a site. Inundated area analysis based on seed algorithm and 3D scene were subsequently adopted with consideration of overflow flooding.

Based on the research results, the key questions raised in chapter 1 and related conclusions are answered and summarized as follows.

1) How to weaken the impact of heterogeneity of weather and underlying surface in a large area?

LIDs are generally used at urban micro sites, and testing and monitoring are main methods for research and analysis of LIDs . On the one hand, the objective of its development is primarily to serve as one of urban land development strategies and urban rainwater management methods. On the other hand, the application on site also satisfies the understanding of the hydrological effect of LIDs, and at the same time can save the costs. However, it is difficult to obtain general conclusions on the application of micro-scale, such as limited by a single land use type, which has hindered the wider application of LIDs. For large-scale application promotion, the first problem to be solved is the influence of climate and underlying surface heterogeneity. In the past, the average method was often used instead of more detailed description. With the development of computer technology, distributed ideas have gradually become practical. For example, a large spatial region with various climatic conditions and underlying surface features is discretized into a number of sub-regions with the same conditions. The sub-regions are studied separately then reintegrated. The higher the degree of dispersion, the more accurate the result is.

In this study, the spatial analysis method of GIS was used to first extract the natural drainage system of the study area based on DEM then calibrated with the actual water system. Based on the distribution of rainfall stations within the study area and the distribution of major rivers, the research watershed was divided into several subcatchments, weakening the influence of climate and underlying surface heterogeneity. The rainfall-runoff module of the distributed hydrological model of SWMM was used to estimate runoff of each subcatchment, and then the runoff of the whole watershed was calculated by the confluence module based on the Saint-Venant equations. Due to the study area is plain and the spatial resolution of DEM is not excellent, the extracted rivers and the actual rivers has certain errors. The manual calibration in ArcGIS is better to improve the results. According to the simulation results, LIDs were deployed in the subcatchments with higher runoff coefficient, providing decision support for the decision-making of the land planning and avoiding blindly to arrange LIDs throughout the entire area. Therefore, through the idea of spatial dispersion and distributed simulation, combining with the GIS spatial analysis method can quickly and effectively solve the problems caused by climate and spatial heterogeneity, reduce errors and improve simulation accuracy. It should be noted that in this study, because of the comparative analysis of the three combined LIDs, the subcatchments were divided according to the main rivers in the study area, and the tributaries were not considered. In general, the more detailed the subcatchment division, the more accurate the results will be, and it is necessary and meaningful for the research or design of the forecast . In addition, SWMM is generally applied to municipal engineering design of urban site. After the generalized watershed and rivers, SWMM was applied to comparative analysis at watershed spatial scale. Through the verification of measured runoff data, SWMM shows a acceptable effect on runoff estimation for larger spatial scale.

2) How to determine the value of input parameters of Storm Water Management Model and how is to use this model in the absence of a completed spatial database?

At present, researchers in many developing countries can't obtain effective spatial data, due to the lack of complete spatial database or limited data sharing level. For example, in China, although the land use database in some cities has been relatively completely and has continuous records, the local government doesn't fully open these spatial databases considering some data privacy issues. In this study, due to the use of simulation method, many spatial parameters need to be input, some of which are based on land use types and distribution, such as imperviousness, initial losses, and so on. In order to solve the problem of lack of land use data, in this study, using remote sensing images that can be obtained freely. Based on digital image processing methods, the main land cover data of the study area was first interpreted and classified, namely the urban area and non-urban area. Classifying only two types is because the DN difference in land cover types between the two types of land is relatively large. High-precision results can be obtained under the condition that the spatial resolution of remote sensing images is not high; on the other hand, one of the main research objectives of this dissertation is urbanization effect on runoff. Classification accuracy of urban area is the main consideration. More detailed types of land cover, such as cultivated land and forest land, were not subdivided. In urban planning and construction, the types of land use in built-up areas will not change in a large area in the long term, except for natural disasters, such as reconstruction after extensive earthquake damage. Based on the classification of land cover and urban planning map of the study area (the data is generally easily available), the spatial analysis methods of GIS were used to extract land use types and distributions in the study area. In general, the use of remote sensing images to interpret and classify land-use data is limited and affected by spatial resolution. For example, for medium-low-precision remote sensing images, due to the influence of mixed pixels and other factors, it is difficult to distinguish detailed and accurate land-use types. Imagery is often used only for rough land cover data extraction. For high-precision remote sensing imagery, it is generally affected by factors such as shades. Of course, both high spatial resolution images and medium and low spatial resolution images require on-site investigations to determine more detailed types of land use, such as commercial areas, residential areas, and so on. Combining urban planning map and remote sensing image data, based on RS and GIS methods, more detailed land use data can be quickly and accurately determined, which is of great significance for hydrological simulation and planning.

The number of parameters of a model mainly depends on the model assumptions. The input parameters of SWMM are less than other hydrological models, but it is still more than the statistical calculation commonly used by municipal design departments. Since this study is mainly a comparative analysis, rougher simulation results with R^2 greater than 0.5 in the basic scenario can be accepted. The estimation of the parameters is mainly based on GIS spatial analysis tools, observational data in the study area, and recommended parameter estimation models by SWMM. Errors are unavoidable, but all are within the control range. The parameter database and evaluation methods for the evaluation of this study still have reference significance for the forecasting and design work of the future.

3) How to describe the process of urbanization in the context of application of Storm Water Management Model?

The concept of urbanization comes from the development of human society. The elements used to describe the process of urbanization are generally based on social and economic aspects. Such as the proportion of the urban population, industrialization, GDP and other single indicators or comprehensive indicators. With the development of the city, its influence has begun to involve natural factors, and the conflict between the city and nature has become increasingly prominent. In the process and results of studying the urbanization effect on natural characters, more natural elements were found to be related to urbanization and has been used to describe the process of urbanization, such as vegetation coverage, soil and topography changes, and impervious surface ratios. In this study, remote sensing method was used to extract the changes of the built-up area in the urban area of the study area every 10 years since 1979. By comparing with the urbanization rate, it is found that the two trends were consistent, which can well reflect the urbanization of the study area. This is mainly because urban construction and planning are generally external expansions. With the increase of urban population, the original residential area cannot accommodate more people, and it is natural to plan and expand outwards, so that the population changes are consistent with urban area changes. In general, actual use and research mostly use population proportion to describe urbanization, besides that they can objectively reflect the urban development process, and on the other hand, because demographic data are easier to be obtained. While large-scale natural geographic features data needs field surveys and mapping and privacy issues are rarely publicly disclosed. With the development of satellite, aerospace, unmanned aerial vehicle technology, and the Internet, more and more natural geographic data can be easily obtained under the globalization of open and big data sharing environments. One is the direct telemetry of sources, and the other is derived from the middle or edge data of the interdisciplinary researches, for example, in this study, although the research objectives are for LIDs, the middle process has obtained many other marginal data, such as land use, soil, impervious rate, runoff coefficient, etc. The changes can also be used to describe the urbanization process. For example, in the study, by comparing the changes of runoff coefficient of each subcatchment, it can be intuitive, with some kind of "quantitative" results to reflect the development direction of the urban area of the research area in the form of "South-North-South". Using geographic features to describe urbanization can not only reflect the characteristics of urbanization itself, but also reflect the impact of urbanization on geographic features and their interactions.

4) How is the effectiveness of combined Low Impact Development Practices in a large area in relationship to extreme storm conditions?

LIDs are the combination of micro engineering measures, characterized by distributed miniature, such as the construction of Rain Barrel, Bioretention or Rain Garden and Vegetation Swale of roadsides and so on. Their application starts from a certain site in the city, in order to solve a particular problem, such as waterlogging effect in the area or rainwater utilization. With further development, even larger area or even entire city would be full of LIDs. What is the impact of LIDs designed originally according to different goals in the entire region? What is the combined effect of LIDs designed with different capacities? In addition, with the impact of urbanization and global climate change, extreme weather occurs frequently around the world. Can LIDs play a good role when encountering extreme storms? In this study, the above issues were discussed through scenario design and simulation. The results show that the effect of the three scenarios on the reduction of runoff volume is greater than the reduction of peak runoff in both the subcatchment and the entire watershed. On the one hand, the effect of the three individual LIDs on the reduction of runoff volume is greater than the reduction of peak runoff. The joint shows the same effect; on the other hand, it also shows that the three LIDs have better control effect on the small runoff than the large runoff. Therefore, although the total runoff decreased, the peak volume reduction was not obviously. The reduction rates in runoff volume and peak runoff in each subcatchment are greater than in the entire watershed. Firstly, because some subcatchments didn’t deploy LIDs, the effect on the entire study area is less than that of all individual subcatchments with LIDs. It might also be due to the fact that the effect of LIDs on runoff control gradually diminishes with increasing spatial scale. Overall, the combination of Rain Barrel, Permeable Pavement, and Rain Garden presented good effect on runoff regulation at the watershed scale, but as the spatial scale increased, its regulatory effect shows a weakening trend. Among the three scenarios, the economic and control efficiency of scenario 1 is the highest. For the future construction of the “Sponge City” in the study area, this scheme of LIDs combination could be given priority. The simulation results of extreme storm scenarios shows that the control effect of the combined LIDs on peak runoff and runoff volume is significantly different under various return periods and duration. With the increase of return period, the effect of LIDs on the peak runoff and the runoff volume is weakening, indicating that LIDs have better control effect on medium and small storms, and have less control over heavy storms; with the increase of duration, LIDs presents the same effect on the peak runoff. The control of runoff volume was also weakening, but it was not obviously.

In addition, under the effect of LIDs, runoff generation time and peak occurrence time of runoff had lags regardless of light storms or heavy storms.

5) How to make planners and decision makers more intuitively and quickly to obtain information of hydrology characteristics and efficiency of Low Impact Development Practices?
LIDs are designed according to their application goals, such as flooding control or rainwater use. Their design is often done by storm management department or municipal drainage department. As they are incorporated into urban planning in many countries or regions, as one of the land development strategies, urban planners or decision-makers require to quickly summarize information from a pile of cross-professional data, although current urban planning practitioners have the ability to interpret data in this area, but in the face of more professional data, it sometimes takes time to digest. In addition, new concepts, new technologies and new requirements have a huge impact on the knowledge structure of relevant professionals, and also lead to some collisions from the planners. With the development of the Internet, some professional aspects that are closely related to the living of the public can be quickly understood by through the form of online sharing and visualized expression. For example, information related to weather or traffic can be quickly obtained through the website or APP of a smart phone. Therefore, visualized, intuitive and easy-to-understand results can not only help planners and decision makers quickly summarize and obtain information, improve efficiency, but also increase participation of the public to provide more suggestions and opinions for the formulation of policy and regulations. In this study, the spatial analysis and visualization technology of GIS were fully utilized. The specialized records were presented in an intuitive and visualized graphical form. On the basis of abstracting the mathematical models, the efficiency of LIDs was expressed using the methods of inundated area visualization and 3D scene, making planners or decision makers more intuitively and quickly to obtain information on runoff characteristics and LIDs efficiency.

6.2 Recommendations and outlook

In the context of urbanization, China has more than 10 million people entering the city every year, and the newly built buildings are equivalent to half of the world's total. Rapid urbanization has led to an increase in the impervious surface, which has led to the loss of urban rainwater resources and an increased risk of flooding in downstream urban area. The current status of urban development in China is that urban infrastructure construction and population quality are not keeping pace with the urbanization. Many cities blindly pursue urbanization rate. Urban planning and municipal facilities construction emphasize on the ground and ignore underground planning and construction. For example, urban storm drainage design standards are low, generally only 1-3 years of return period. In addition, due to the large population density and poor quality, the municipal facilities in some areas are severely damaged and cannot be used for good functionality. For example, many rainwater pipelines or inlets are blocked by domestic garbage, and river sheds have severely reduced flood discharge capacity of river channels, which leads to frequently flooding or waterlogging cased by medium or small storms. Some ideas, new technologies, and new requirements have a huge impact on China's urban storm management system and professional knowledge structure. In the specific implementation process, it has encountered many complex problems and bottlenecks.

In response to the current problems in China and the simulation results of urbanization effect and LIDs efficiency in this study, some suggestions are proposed as follows: 1) strengthen infrastructure construction, increase public awareness, and avoid blindly pursuing urbanization rate while ignoring basic construction and citizen quality education. In particular, for the planning and construction of new urban development area, the local government must strengthen management and increase law enforcement; the planning and design departments should improve the standards for urban rainwater infrastructure construction based on local rain characteristics; 2) to avoid the blindly and completely excavation for the pipeline upgrade in built-up area, it should be combined with the actual conditions of each city, combined with the planning of the transformation of old cities, road expansion. Although LIDs can control or regulate runoff, their effect on heavy storms is still limited. While considering sustainable development and runoff objectives, LIDs should be used in conjunction with drainage system upgrading to build a “green-gray” coupling system, based on their characteristics to play a full role; 3) develop a clear and feasible near-term retrofit plan, make full use of GIS, RS and modeling methods supported by modern computer technologies to perform multiple simulations and assessment of existing regional drainage capacity, intrinsic risk, and LIDs design layout. When the optimal plan is produced, on-site practice can be conducted, to avoid reworking or wasteful working due to design problems, resulting in unnecessary economic losses. It is necessary to more effectively use existing facilities and their surface drainage capacity, realizing small-scale design, large-scale comparative analysis; 4) protect existing green vegetation and natural water bodies, and reconstructing or adding LIDs based on that, and use existing geographical factors of built area as many as possible, such as local soil and vegetation, avoiding the occurrence of damage to other factors due to certain goal. For example, straightening the river for quickly draining runoff or flooding but damaging the natural ecosystem. It is imperative to strictly implement sustainable development strategies; 5) for extreme storms, sometimes due to the limited capacity of urban flood discharge or inadequate urban development funds, in the event that the rainwater drainage system couldn't effectively discharge floodwater, it is necessary to make full use of new technology means, such as the temporary anti-flood wall which is often used in some cities of Germany. Reasonably use roads to transport floods, and establish effective emergency measures to reduce loss of life and property. 6) integrate GIS, RS with hydrological models to develop a comprehensive management system with monitoring, hydrological information management and processing, hydrological simulation and evaluation, and visualized output functions, such as PC software or mobile phone APP, to achieve efficient digital visualization management, minimizing the conflict between interdisciplines and providing planners, decision makers and the public with a platform for quickly and effectively accessing and summarizing information.

The integrated idea of GIS、RS and hydrological modeling used in this study has demonstrated to be available in evaluating and analyzing effectiveness of combined LIDs consisted of Rain Barrel, Permeable Pavement and Rain Garden in Jinan city and in providing a support for decision making processes towards a sustainable development. Some meaningful results provide a better understanding of urbanization effect on runoff and LIDs effectiveness. However, there are several limitations and shortcomings that should be recognized regarding present study. In order to get more information to support the sustainable development, some other ideas may also be considered in the further study.

In this study, the result of runoff simulation, a basis of effectiveness evaluation of LIDs, is acceptable for a comparison analysis in a large spatial scale area. It doesn’t present a higher precision due to the reasons as follows: the division of the watershed and rivers abstraction in SWMM only considered the distribution of main rivers because of the lack of more detailed data of the tributaries; daily runoff records of six years was used to verify the model, theoretically more records such as at least 30 years, and with less time step are the best, especially for designing and forecasting study. More detailed sub-area divisions and measured records over years could improve simulation accuracy and enhance simulation quality. The three combined LIDs scenarios were produced mainly based on impervious surface ratio that LIDs deal with. The effect of the interaction of LIDs weren’t simulated because modeling of the hydraulic interaction between LIDs in SWMM requires each LID practice to be set as a separate subcatchment based on their spatial distribution, while the number of deployed LIDs were large due the spatial scale of the study area. If took the each LID practice as a independent subcatchment, it would took much time. Although the more detailed consideration of LIDs will not impact the simulation results so much, it could help to understand the interaction between LIDs and further improve the scenario design of combined LIDs. In the future research, one could consider to improve the LIDs module of SWMM to develop independent LIDs object that doesn’t rely on the subcatchment object. At the same time, to develop certain function to directly drag or move LIDs object to facilitate use and rapid layout. Model simulation generally requires many parameters. Although SWMM has fewer parameters than other models, in this study, it still took a lot of time to estimate these parameters. With the development of open sharing database, many spatial and statistical data can be obtained directly on the Internet, such as the Explorer system provided by USGS, and some online databases of precipitation estimation based on remote sensing images analysis. The parameter database of the hydrological model has also been gradually developed. For example, in the application of the SWAT model, many Chinese institutes has established the SWAT parameter database of main cities of China. With the more applications of SWMM in China, the establishment of parameter database should also be further developed, which would greatly improve the efficiency and widely application of SWMM.

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EIDESSTATTLICHE VERSICHERUNG

Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertationsschrift zum Thema

“Analysis and evaluation of the effectiveness of Low Impact Development practices on runoff control using Remote Sensing, GIS and hydroiogicai modeling”

selbstständig verfasst und keine anderen als die angegebenen Quellen benutzt habe. Alle Stellen, die wörtlich oder sinngemäß aus Quellen entnommen wurden, habe ich als solche gekennzeichnet.

Des Weiteren erkläre ich an Eides statt, dass diese Arbeit weder in gleicher noch in ähnlicher Fassung einer akademischen Prüfung vorgelegt wurde.

Dortmund, 11.02.2019 Yan Chen