Urban Water-log Simulation and Prediction based on Multi-Agent Systems

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Abstract

Urban water-logging often occurs along with rapid urbanization and becomes a huge challenge on drainage emergency decision in many Chinese cities. Due to lack of the functionality for process modeling in terms of simulation in GIS, this paper proposed a method of agent-based water-logging simulation and prediction. Because of the fragmentation and space complexity on urban surface, urban water-logging is predicted based on simulating by multi-agent systems instead of traditional hydrological equations. The method can simulate uncertain flow and calculate water depth of any position at any moment, and seek optimal reservoirs for storing the excessive floods. Many factors of rainfall, flow, sink, interception, infiltration, gully outflow are considered, and multi-agents of water-log, drainage system and environment are utilized. Interaction rules among agents are defined. This approach is verified by historical data in DongHaoChong basin, central urban of Guangzhou city, and applied to forecast water-logging with a 100-year storm. The geocomputation process is supported by NetLogo tool system, an agent-based programming language and integrated modeling environment. The results are compared with those of a CA model developed in Matlab. The improvement of the methodology is discussed with respect to rules, parameters and data accuracy. The experiments demonstrated that the method is efficient for modeling the process of urban water-logging and drainage optimization to decrease huge loss of life and properties.

Keywords: Urban water-logging; Surface water simulation; Agent-based model; Multi-agent; Netlogo system.

1. Introduction

Agent-based modeling and simulation becomes increasingly popular in social sciences, due to its elegant and explicitly represent entities, environment, and relations between them (Gilbert, 2008). Although many agent-based models were built to simulate the complicated urban phenomena, few are done for urban water-log. In recent years, urban water-logging is very frequent in many cities that have long been a major concern in various areas throughout the world. Alongside rapid urbanization in People's Republic of

China, over 100 out of 656 cities suffer from water-logging in various degrees, while urban flooding is caused by the uneven distribution of precipitation in time and space and the disappearance of flood plains (Asia Development Bank, 2014). August 26th 2014 a rainstorm hit Guang'an City, southwest China's Sichuan Province, causing a serious urban water-logging by Xinhua News. May 14th 2013 Nanchang city, capital of East China's Jiangxi Province was hit by a heavy rainfall and occurred urban water-logging published by Xinhua News. In July 2007 the heaviest rain in the last 115 years brought 266.6 millimeters of rainfall within 24 hours in Chongqing, and this tremendous amount of rain caused heavy flooding and water-logging which led to a death toll of more than 50 people and an economic loss of more than CNY2.1 billion. In the same month, a historically heavy rain in Shandong Province's Ji'nan city claimed the lives of 37 people and led to an economic loss of CNY1.2 billion. Similarly, heaviest ever rainfall occurred in Dhaka City and its devastating impacts paralyzed the city life September 11th to 16th 2004 (Tawhid, 2004). At the same time, urban storm-water management and water-logging prevention lag infrastructure building in many cities, and drainage pipes are insufficient or poorly maintained while design standards of the storm-water system are not up-to-date. Thus, it is necessary to simulate and forecast urban water-log as a low-impact development (LID) measure to prevent huge loss.

There are many related studies that involve urban surface water simulation. A number of applications have been conducted by the USGS Missouri Water Science Center in conjunction with ecological and flood studies in Missouri to simulate the movement of water and sediment in rivers, lakes, and coastal waters using a two-dimensional stream flow model (Heimann et al., 2006). Elliott and Trowsdale (2007) reviewed ten existing storm water models which were all based on conventional methods for runoff generation and routing, but half of the models add a groundwater/base flow component and several include infiltration from LID devices. Several models are capable of modeling distributed on-site devices with a fine temporal resolution and continuous simulation, yet further research should address the need for such temporal and spatial detail, and linkage to automated calibration and prediction uncertainty models at a catchment level. Microcosmic CA which was introduced in 1948 by von Neumann and Ulam has attracted the attention of researchers in geography, ecology and other environmental sciences because of their powerful ability to model and visualize complex spatially distributed processes (Li et al., 2013; Takeyama and Couclelis, 1997; Xia and Gar-On, 2002). Tang et al. (2010) developed a distributed hydrological model based on CA to simulate the rainfall-runoff process in the Chabagou watershed in the Loess Plateau region of the Yellow River Basin. Cirbus and Podhoranyi (2013) simulated the spreading of liquid using a CA and comparatively simple rules and conditions. Liu et al. (2014) developed a 2D CA model with Von Neumann neighborhood to simulate flood inundation on urban roads.

However, the flow across fragmental urban ground is difficult to be exactly expressed through the traditional rainfall-runoff models based on discharge equation or momentum equation or energy equation. Agent-based model include agents, environment, and relations between them, with providing the intuitive observation of interactions and urban phenomena resulting from them. Agent-based approach also allows for very explicit modeling-entities from the real world can be directly represented in the model. It is also possible to represent heterogeneous entities and environment in the model, as well as model intelligent synchronous behavior of entities. Thus, this paper aims to build an agent-based model to simulate urban water-logging.

2. Multi-agent models

Multi-agent system is a system composed of environment, objects (passive elements of the system), agents (active elements of the system), relations between different elements, set of operations which allow agents to observe and interact with other elements of the system (including other agents), and operators which aim is to represent agent’s actions and reactions of the other elements of the system. In this study, two agents of water flow and water-log are designed to represent the motive elements during storm, and drainage system is passive elements. Environment includes rain fall, ground sink, plant interception, soil infiltration. Agent of flow in time t is described as following structure:

Agentflow(t) = <velocity(t), flowdir(t), length(t), grow, merge, divide, die> (1)

Here, velocity (t), flowdir (t) and length (t) are attributes of Agentflow at time t. The grow, merge, divide, and die are actions of the agent. If both of flow velocity and depth on adjacent cells in environment are beyond threshold value, an Agentflow is created. Otherwise, it will die. An agentflow can grow and merge with similar adjoining Agentflow.

AgentWaterlog(t) = <depth(t), volume(t), area(t), refresh, die> (2)

Here, depth(t), volume(t) and area(t) are dynamic attributes of AgentWaterlog. If depth, volume and area on adjacent cells in environment are beyond threshold value, an AgentWaterlog is created. Otherwise, it will die.

ObjGully(t) = <height, size, flow coefficient, block coefficient, discharge> (3)

Gully as object has 4 static attribute, but dynamically discharge water according following equation (4).

$$g(t) = \mathrm{W} * C * k * \Delta t * \sqrt{2g * \mathrm{depth}(t-1)/1000} \qquad (4)$$

Where W is the surface area of drain gully in current cell (m2), C is flow coefficient of gully, and K is blocking coefficient of gully, and g is the gravitational acceleration constant, h(c,t) is the previous water depth on the gully(mm).

Env(t) =< dem, land use, ground sink, plant interception, water depth(t), rain fall(t), soil infiltration(t)> (5)

The element of environment(t) is cell, similar to the patch in Netlogo, which have static attributes, dynamic attributes and actions. Static attributes on every patch keep its value during simulation, such as height, land use type, ground sink, plant interception. Value of dynamic attributes on every patch varies as time goes on, including rain fall, soil infiltration, water depth. The soil infiltration loss is calculated by the Horton’s equation (Ma et al., 2009).

3. Water-log simulation

3.1 Study area and data

DongHaoChong basin is selected as the study area, which locates in central urban of Guangzhou, in southern China, shown in Fig.1a. Its center is (113^{0}17’E, 23^{0}8’N), and whole catchment area is about 11 square kilometers. The north is higher than south in the basin, its DEM is shown in Fig. 1b. DongHaoChong canal is a main branch of Pear river in Guangzhou City, with full length 4,225 meters and width 7-11 meters, which originates in LuHu lake in the south of Baiyunshan mountain. The canal flows through traditional urban of Guangzhou from north to south, and had brought big floods decades ago. Now because of high density of buildings and obsolete drainage facilities, the DongHaoChong basin is often subjected to heavy water-log during storm. The study area is shown in Fig.1.

Fig.1a. Study area location in Guangzhou urban

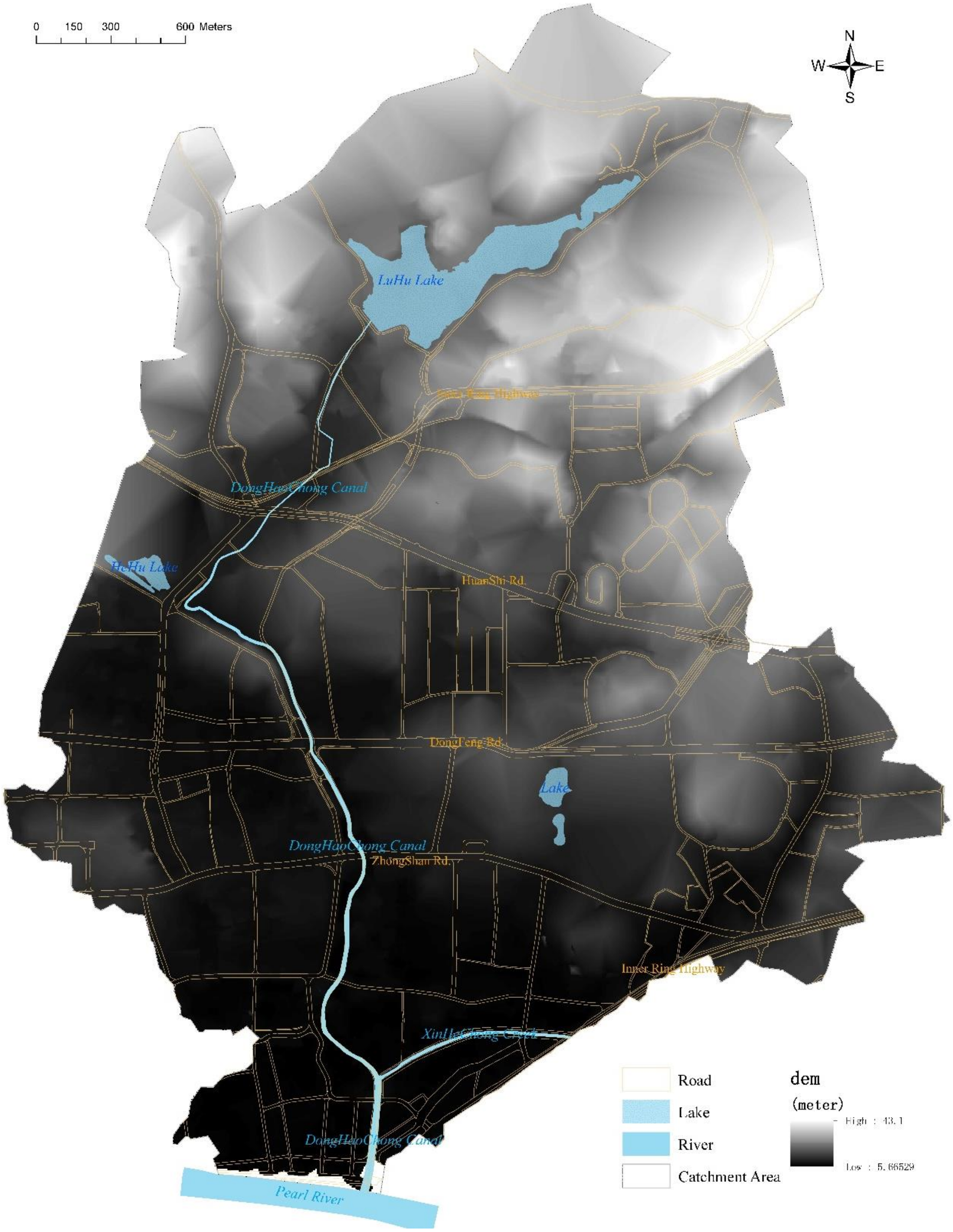

Fig.1b. Dem, river and main roads in study area

Spatial data and parameters related with agent-based model as listed in Table 1. All source data came from drainage facilities management center in Guangzhou, including DEM, green land, building, road, reservoir, lake, river, drain gully, rainfall, and so on. The DEM is divided into 790,860 square grids in 980 columns and 807 rows with 5 meters resolution. The land cover layer is composed of the green land, building, road, river and lake. Gully is a part of sewer systems in urban environment. Gully data is geographic point vector, with geometry point location and some attributes, such as surface size and block coefficient. The rainfall is time series data from observation or prediction, assuming that the rain is well-distributed in small scale. Manning coefficient, MC, is used to calculate the flow velocity on different land cover by Manning equation. Three Horton parameters are used to calculate the infiltration amount on permeable surface. I(c) is interception by plant on permeable surface and S(c) is sink constant when water flows on ground. Flow coefficient C depends on the shape of gully, and block coefficient indicates the blocked rate on gully. The values of parameters are revised to minimize the deviation between observations and simulation results, most of which are initialized and tested based on empirical value (Fuping et al., 2010; Schaffranek, 2004; Valipour, 2014).

Table 1. The list of main data source and parameters

Name	Data type	Value or value type	Unit	Notation
DEM	Grid data	double	meter	Resolution 5m, 980*807
Land cover	vector data	inter		
gully	point			0 no gully, 1 gully
rainfall	time series data	double	mm	depends on rain duration
Mn	Manning coefficient	0.21		permeable surface
		0.012		impermeable surface
f_c	Horton para.	0.055	mm /min	permeable surface
f_0	Horton para.	2.483	mm /min	permeable surface
λ	Horton para.	4		permeable surface
I(c)	interception	2.5	mm	permeable surface
S(c)	Sink constant	1.5	mm	permeable surface
		3.6	mm	impermeable surface
C	flow coefficient	0.8		round gully
		0.6		square gully
K	block coefficient	2/3		gully block coefficient

3.2 Results and validation

Here, we use two typical rainfalls accompanied with heavy water-log to test the agent-based model in study area. The storm caused by typhoon Ute on Aug 15, 2013 lasted 14 hours and brought about half of the study area flooding in some degrees. The rainfall in previous 5 hour is chose to simulate, for its amount is 64% in total rainfall. The rain on Jun 23, 2014 is a heavy thundershower, resulted in an obvious water-log in study area. The rainfall data is monitored by Guangzhou Weather Bureau, shown in Fig.2.

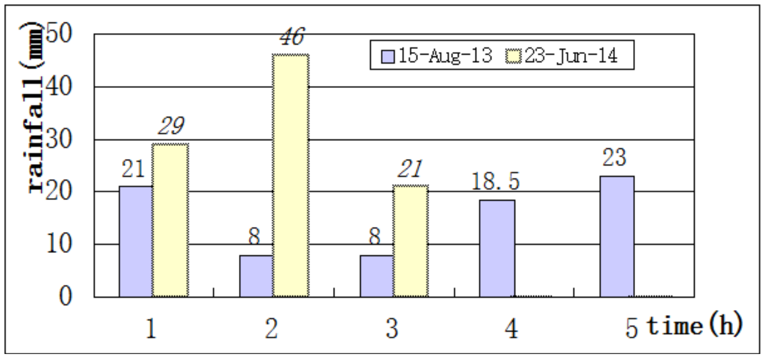

Fig.2. The rainfall per hour in two rains

The simulation results of two rains at the final time by Netlogo are shown in Fig.3a and 3c. The water-log in Fig.3c has similar distribution in Fig.3a, but it is obviously serious because the rainfall on Aug 15, 2013 is smaller and its duration is longer than the rainfall on Jun 23, 2014. Some main flooded areas are observed by Drainage Facility Management Center in Guangzhou. Although most observed points usually locate at roads, their position approved that the distribution of simulation water-log is credible. Fig.5c and 5d state clearly also the simulated depth is very close to the observed depth. Most of simulation values are just a little below the observed depths, which may be influenced by some factors and be discussed later.

Fig. 3a. The agent-based result simulated by Netlogo for storm caused by typhoon Ute on Aug 15, 2013

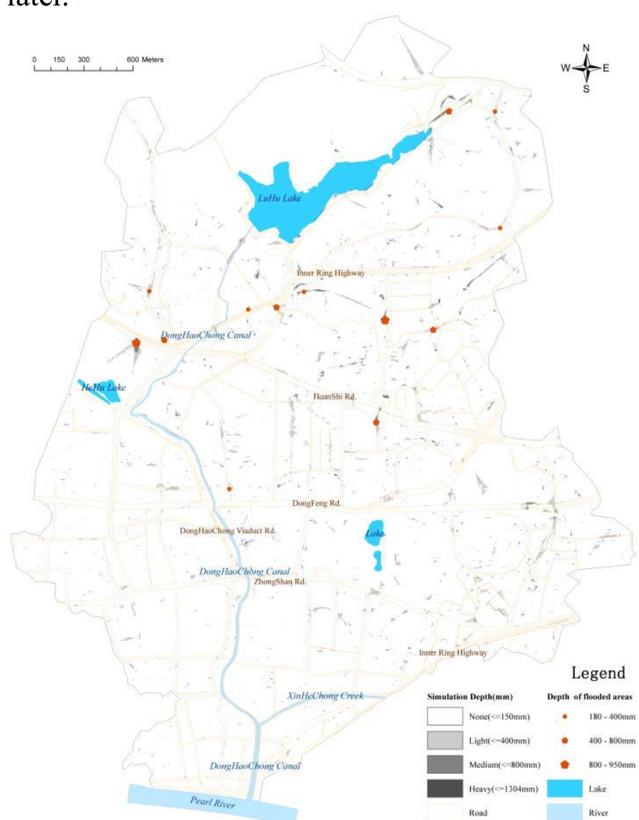

Fig. 3b. The result simulated by CA model for storm caused by typhoon Ute on Aug 15, 2013

Fig. 3c. The Agent-based result simulated by Netlogo for thundershower on Jun 23, 2014

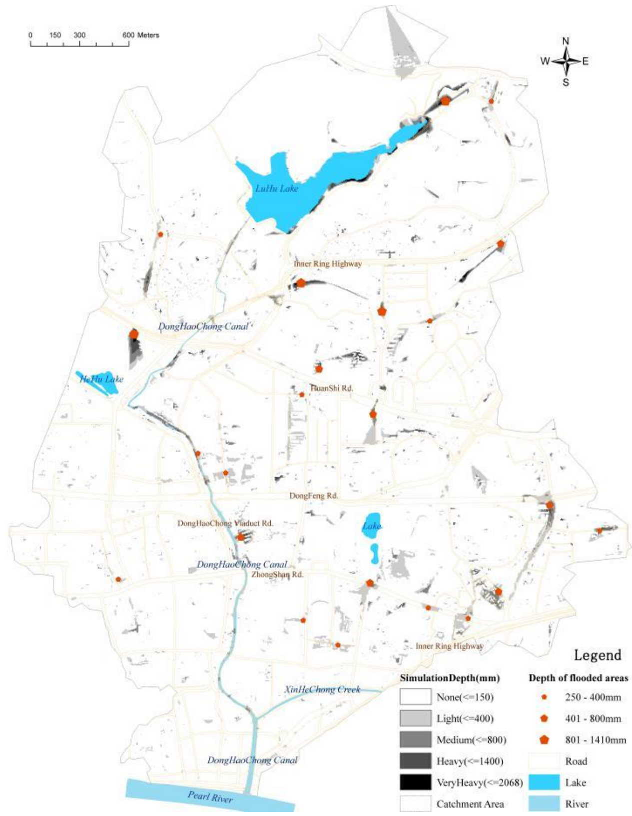

Fig.3d. The result simulated by CA model for thundershower on Jun 23, 2014

4. Conclusion

The paper proposed a method of simulating urban water-logging based on multi-agent. For the fragmentation and space complexity of urban surface, urban water-logging is simulated using multi-agent model instead of mathematical runoff equations. The multi-agent model in the study could simulate uncertain flow at any position and predict water-log depth at any moment with inputting DEM, land use, gully, and rainfall, etc. The results of urban water-logging are compared with simulation by CA model at DongHaoChong basin in Guangzhou, China. The multi-agent model can remedy the limitation of CA simulation, such as step time deviation, lack of reciprocal effect between the factors of water-log.

5. Acknowledgements

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