

Analysis and Simulation of Drainage Capacity of Urban Pipe Network

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Abstract: With the rapid development of urbanization, impervious areas spread quickly, which have greatly influenced regional hydrology and water resources. The water quality is getting worse and worse. The flood and drought disasters have aggravated. Human living environment has changed and consequently sustainable development of economy is restricted. The drainage pipe network plays a very important role in urban drainage and flood control. In the study, using of computer technology, the drainage capacity of study area in different design rainstorm return periods ($P = 0.25, 0.5, 1, 2, 5, 10$ a, respectively) is analyzed and simulated by Storm Water Management Model (SWMM). Part of the pipe network that are filled slowly and change great are found out fewer than 6 design rainstorms, which provide the basis for reconstruction of urban conduits. The simulation results can provide strong technical support for the city drainage system planning and management.

Keywords: Drainage capacity, modeling, numerical simulation, pipe network, SWMM

INTRODUCTION

Due to the urbanization, the city population and the impervious areas are increasing. These two parts will also lead to other aspects of problems. First, the precipitation that falls on impervious surfaces becomes surface runoff which is connected directly to the sewer network. This will increase peak flows and decreases peak flow lag times. The drainage system must be able to cope with the increased peak flows to reduce potential damage and inconvenience. But the initial sewer network's capacity has been not enough to contain all the runoff from surface; the exceeding surface runoff will cause urban flooding. Second, because of the large city and its population, the demand of water resources will also increase sharply.

The drainage network as an important and indispensable infrastructure for city, which is using for city Underground Drainage, drainage, flood control works. With the accelerating progress of urbanization, drainage task assumed by the drainage network become heavier. In many cities, the existing drainage network due to the construction of age-old design, the drainage capacity is lack (Parka *et al.*, 2008); drainage capability can no longer meet the increasing demand of urban land

use changes and city construction. Face this issue, the drainage network in many cities start to redesign and transformation, in order to meet the needs of the city's drainage capability.

In this background, the storm water management model (referred to as the SWMM model) has been applied in this study; the drainage capability in design storm conditions of Yuhua District in Nanjing city was simulated. Through simulation, provide the basis for the design and reconstruction of the actual pipe network, to avoid the city water logging disaster.

BASIC THEORY OF SWMM

The EPA Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. It was used in Tianjin and Shanghai city (Liu and Xu, 2001). This model is mainly used in small cities' runoff and water quality forecasting, river drainage simulation and compute and drainage pipe network system verification and management. It consists of runoff yield model, infiltration model, surface runoff concentration model and pipe hydraulic dynamic model (Wang and Xu, 2008).

RUNOFF YIELD MODEL

The process of rainfall turning into net rain is called runoff yield. Based on the land use status and surface drainage directions, study area is discretized into several sub catchments. According to the hydrology differences, each Sub catchment can be divided into pervious and impervious sub areas. Surface runoff can infiltrate into the upper soil zone of the pervious subarea, but not through the impervious subarea. Impervious areas are themselves divided into two subareas - one that contains depression storage and another that does not. Those three subareas' runoff yield is computed separately and the sub catchments' runoff is the sum of subareas.

Infiltration model: Infiltration is the process of rainfall penetrating the ground surface into the unsaturated soil zone of pervious sub catchments areas. SWMM offers three choices for modeling infiltration: Horton's Equation, Green-Ampt Method and SCS Curve Number Method. Horton's Equation mainly describes the relationship that infiltration intensity changes with rainfall duration and does not reflect the underlying surface status of saturated and unsaturated zone. Green-Ampt Method assumes that a sharp wetting front exists in the soil column, separating soil with some initial moisture content below from saturated soil above. A sufficient rainfall and infiltration process can make the soil saturated. SCS Curve Number Method assumes that the total infiltration capacity of a soil can be found from the soil's tabulated Curve Number. During a rain event this capacity is depleted as a function of cumulative rainfall and remaining capacity.

Surface runoff concentration model: The task of surface runoff concentration is to convert the subareas' net rainfall process into sub catchments' discharge process. In SWMM, this task is realized by making three subareas approximated as nonlinear reservoir. Namely, solving continuity equation and Manning Formula simultaneously. It is a lumped model.

Pipe hydraulic dynamic model: The pipe flow routing in SWMM is calculated by conservation of mass and conservation of energy formula. And three solving methods are supplied: Steady Flow, Kinematic Wave and Dynamic Wave (Rui, 2004):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = \quad (1)$$

$$\frac{Q}{gA} \cdot \frac{\partial}{\partial x} \left(\frac{Q}{A} \right) + \frac{1}{gA} \cdot \frac{\partial Q}{\partial t} + \frac{\partial h}{\partial x} + S_f - S_0 = 0 \quad (2)$$

where,

- Q = Discharge, m³/s
- A = Area of the wetted cross section, m²
- h = Pipe water depth, m

- t = Time, s
- x = Pipe length along the water direction
- S_f = Resistance slope
- S₀ = Pipeline slope

- **Steady flow:** Steady Flow routing represents the simplest type of routing possible (actually no routing) by assuming that within each computational time step flow is uniform and steady. Thus it simply translates inflow hydrographs at the upstream end of the conduit to the downstream end, with no delay or change in shape. The normal flow equation is used to relate flow rate to flow area (or depth).
- **Kinematic wave:** This routing method solves the continuity equation along with a simplified form of the momentum equation in each conduit. The latter requires that the slope of the water surface equal the slope of the conduit. The maximum flow that can be conveyed through a conduit is the full normal flow value. Any flow in excess of this entering the inlet node is either lost from the system or can pond atop the inlet node and be re-introduced into the conduit as capacity becomes available. Kinematic wave routing allows flow and area to vary both spatially and temporally within a conduit. This can result in attenuated and delayed outflow hydrographs as inflow is routed through the channel. However this form of routing cannot account for backwater effects, entrance/exit losses, flow reversal, or pressurized flow and is also restricted to dendritic network layouts. It can usually maintain numerical stability with moderately large time steps, on the order of 1 to 5 min. If the aforementioned effects are not expected to be significant then this alternative can be an accurate and efficient routing method, especially for long-term simulations.
- **Dynamic wave:** Dynamic Wave routing solves the complete one-dimensional Saint Venant flow equations and therefore produces the most theoretically accurate results. These equations consist of the continuity and momentum equations for conduits and a volume continuity equation at nodes. With this form of routing it is possible to represent pressurized flow when a closed conduit becomes full, such that flows can exceed the full normal flow value. Flooding occurs when the water depth at a node exceeds the maximum available depth and the excess flow is either lost from the system or can pond atop the node and re-enter the drainage system. Dynamic wave routing can account for channel storage, backwater, entrance/exit losses, flow reversal and pressurized flow. Because it couples together the solution for both water levels at nodes and flow in conduits it

can be applied to any general network layout, even those containing multiple downstream diversions and loops. It is the method of choice for systems subjected to significant backwater effects due to downstream flow restrictions and with flow regulation via weirs and orifices. This generality comes at a price of having to use much smaller time steps, on the order of a minute or less (SWMM can automatically reduce the user-defined maximum time step as needed to maintain numerical stability).

Each of these routing methods employs the Manning equation to relate flow rate to flow depth and bed (or friction) slope. The one exception is for circular Force Main shapes under pressurized flow, where either the Hazen-Williams or Darcy-Weisbach equation is used instead.

THE APPLICATION OF SWMM IN STUDY AREA

The surface area, catchment area width, slope gradient, the Manning roughness coefficient, infiltration rate, the length of the pipeline, pipeline diameter and other data is necessary input of the model. In order to evaluation the drainage capacity of the study area, first need to build model of the research area. The study area

is located in the Yuhua District, Nanjing, Jiangsu Province, which an area of 950.28 ha, an average gradient of 4.67%, including residential area accounted for 28%, road area accounted for 9.98%, other land and green area accounted for 62.02%.The drainage capacity of the study area as Fig. 1.

Subcatchment division: Need to division the study area when use the swmm model to simulation, which process including division the whole catchment into several sub-catchments and generalization each sub-catchments hydrological characteristics. In the cities, existence of real sub-catchment areas, but due to the development of the city's own characteristics and urbanization change of surface condition, so leading to determine its true sub-catchment areas become difficult. If reasonably determine the sub-catchment areas, makes the model simulation results to better fit the actual situation. In order to better divide sub-catchment areas and try to simplify the model input data in the condition of ensure its simulation accuracy, this study use an approaches combination the road and DEM of the study area. Through the method using the Hydrological Analysis division the study area and then using the land use map with artificial merger and adjustment, which final completion the division of the sub-catchment

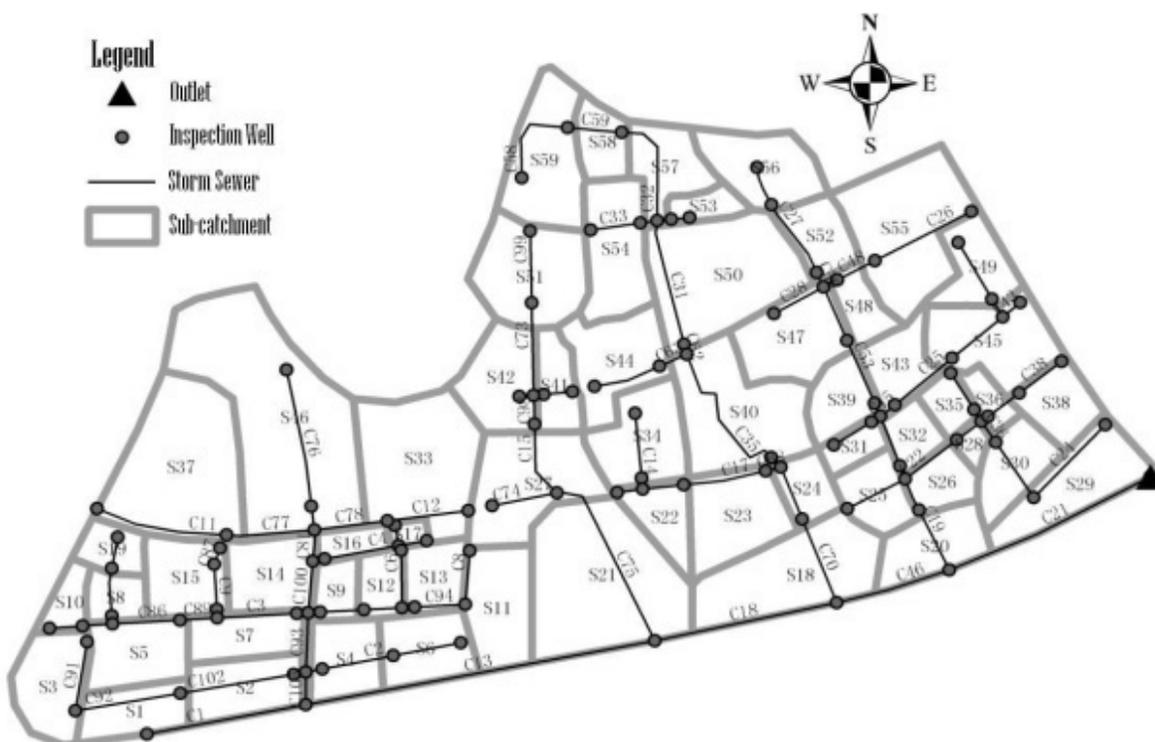


Fig. 1: Drainage system of study area

areas. When determined the sub-catchment areas, then use the geostatistical module in ArcGIS to calculate the slope, area, SWMM model parameters, of each sub-catchment areas, which provide a reliable and fast guarantee for build the model (Tang and Yang, 2006).

Model parameter calibration: SWMM parameters can be divided into two kinds: surface input parameters and pipe input parameters. Surface input parameters in this area consist of : characteristic width of the overland flow path for sheet flow runoff, area of the sub catchment, Percent of the impervious land area, average percent slope of the sub catchment, Manning's n for overland flow over the sub catchment including the impervious portion and pervious portion, depth of depression storage and infiltration parameters. Pipe input parameters consist of: conduit cross-section, conduit length, Manning's roughness coefficient, maximum depth of the conduit's cross section, conduit elevation. Because water lagging, water concentration time and outflow hydrograph are affected by W (characteristic width of the overland flow path for sheet flow runoff), W is temporarily fixed as a constant, using the real rainfall event to calibrate.

Rainfall data selection: Using SWMM model to simulate the rainfall data is very importance, especially when the rainfall data can reflect the actual rainfall; this rainfall data will improve precision of the model simulation results. Different regional climate differences and resulting differences in rainfall patterns, law of distribution of rainfall is suitable for what kind of curve, which requires a lot of statistical analysis on the basis of summed up. Commonly used synthetic storm model approach has Huff, CHM, PC and YC (Xu, 2009). In the domestic applicability of better synthetic rainstorm model is Chicago synthetic storm hydrograph (CHM method), it is by of Keifer and Chu (1957) storm sewer system in Chicago put forward a synthetic rainstorm process line. In recent years, many regions through the heavy rain observation data of arrangement put forward the suitable for all heavy rains in strength formula. Access to relevant information, according to the Meteorological Research Institute of Nanjing storm intensity formula, select the study area storm intensity formula as follows:

$$q = \frac{2989.3(1+0.6711gp)}{(t+13.3)^{0.8}} \quad (3)$$

where

- q = Rainfall intensity, L/(S.hm²)
- p = Design rainfall return period, a
- t = Duration of rainfall, min

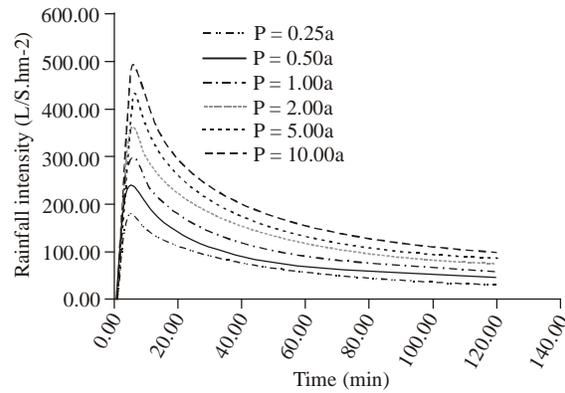


Fig. 2: Different frequency distribution of storm intensity

In China, the storm sewer design return period is generally used in 1 to 3, for important areas, generally used in 2 ~ 5a. In order to test the drainage capacity of the pipeline network in the condition of different frequency rainstorm, using the type (3) seek the return period $P = 0.25$ a and 0.5, 1, 2, 5, 10 a, respectively heavy rain intensity distribution, as shown in Fig. 2. According to the storm intensity, seek the corresponding frequency of rainfall process line. Rainfall used in the simulation time interval of five minutes, the rainfall lasted for 1 h, calculate the corresponding frequency of rainfall is 34.14, 45.71, 57.28, 68.85, 84.14, 95.71mm, respectively.

SIMULATION RESULTS ANALYSIS

In order to analysis the drainage capacity of the study area, this study selecting the check wells and pipelines simulation results. The result of the time series is for every 5 min read and the total time is 6 h.

Analysis of water depth in check wells: When drainage pipe network's load is too large, the check wells was easy to produce water, also was likely to exceed its maximum drainage capacity. So check the well's water depth can be used as an indicator to reflect the drainage capacity of the pipe network. Figure 3 shows inspection wells node J1 - J108 which connection the network C13, C18 and C46 in the case of 10a's rainstorm the water depth of the check wells and pipe network. Through the figure can see the condition of the drainage pipe network.

The study area contains 109 check wells; each inspection wells have a maximum allowable depth and exceeds the maximum allowable depth of rain is easy to overflow. In the different frequency of heavy rain conditions, according to the simulation results, can be drawn from the wells of each check node maximum

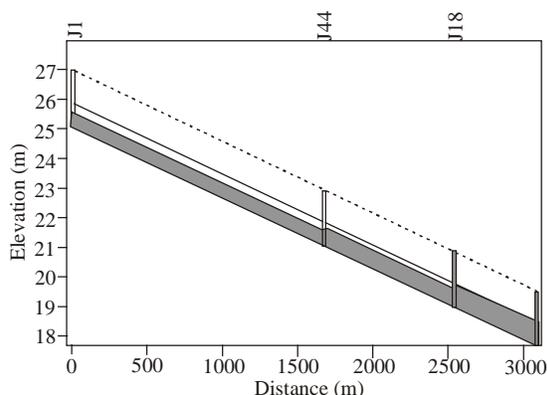


Fig. 3: Water elevation profile: NodeJ1-J18

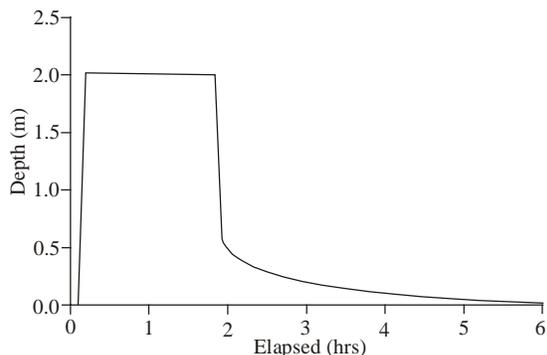


Fig. 4: Water depth of node J 18

Table 1: The see per time of J 24 and J 18

P/a		0.25	0.5	1	2	5	10
J24	M time/h/min	0:11	0:10	0:10	0:10	0:10	0:10
	Average/depth /m	0.17	0.18	0.18	0.18	0.19	0.19
	Duration time /min	4.2	4.3	4.5	4.6	4.7	4.8
J18	M time/h/min	0:07	0:07	0:07	0:07	0:06	0:06
	Average depth /m	0.45	0.45	0.46	0.47	0.48	0.49
	Duration time /min	73.8	74.4	76.2	78	81	82.2

Table 2: The time of surcharge conduits

Number		P/a					
		0.25	0.5	1	2	5	10
Full low time /min	t = 0	21	15	13	11	10	8
	0<t<= 30	43	35	33	33	31	33
	30<t<= 60	22	24	21	11	5	5
	60<t	22	34	41	53	62	62

depth of occurrence time and duration time. There are two type inspections well; one is connected to a single pipeline and the other connecting section of the pipeline. Table 1 is the result of the connection of single and multistage pipeline which the name is inspection wells J 24 and J 18 contain the average water depth and maximum depth of duration in the different frequency of heavy rain conditions. Figure 4 is

a diagram of the inspection wells J 18 in the conditions of $P = 10$ a design storm conditions, the water's depth change figure. Be seen from the statistical results, J 24 and J 18 of the maximum depth of approximately the same time in different rainstorm case. This is mainly due to using Storm Data rain type peak on the first few minutes, resulting in the maximum depth of the check wells in about 10 min. Contrast the biggest water depth duration and average water depth, J 18 is far larger than J 24. Exists the difference is mainly J 24 inflow mainly from sub-catchment area of rain water through surface runoff into the pipe, but J18 in addition to the inflow catchment areas, as well as other multi-stage pipeline convergence. Evaluation of regional drainage capacity, J18 type checking wells can be used as an important basis. In the condition of $P = 0.25a, 0.5a, 1a, 2a, 5a, 10a$, obtain the proportion of the total of the time or more than one hour of inspection wells were 14.7, 17.4, 23.9, 32.1, 38.5, 41.3%, respectively of which the longest duration of nearly 2 h. The maximum water lasted for more than 1 h of this part of the inspection wells, which connection's pipeline networks are playing a key role in the transformation of the drainage of the study area. This part of the pipeline network reconstruction is very important.

Analysis of drainage capacity: The result of the check well can reflection part of the condition of the pipe network, but detailed situations should be the state analysis on pipeline network for water. The study area has 108 pipes and the total length is about 31 km. Pipeline flow in the duration of the full flow state is called the pipeline full flow time and pipeline full flow time can reflect the drainage load of the pipe network. When the full flow a long time, on the ground may have serious water and which explain that the drainage capacity of the pipe network was inadequate. In the condition of $P = 0.25, 0.5, 1, 2, 5, 10 a$, respectively the pipeline full flow time was different. The Table 2 is the pipeline full flow time distribution range tale.

Full flow time distribution range tale. Combined with Table 2, we can see that the pipe network of the study area in the case of different frequency design storm, with the increase of rainfall intensity, the pipeline full flow time becomes longer and number was increase. From the statistics result, when p is small, 20.4% of the pipeline in study area full flow a long time, as P increases, 57.4 percent of the pipeline full flow a long time. This 57.4% of the pipeline played a limited role to the research area. Find out this part of the pipeline, combined with the parameters and the position in the drainage pipe, can be found that the main reason for this is to produce a larger catchment area, a smaller pipe diameter and slope. Such as the

main drainage channels C56, diameter of only 400mm, the slope is only 0.002, but bear the confluence of several sub-catchment areas. Through simulation, we can see that the problems of the existing pipe network of the study area, mainly due to the lack of pipe drainage capacity, thereby affecting the drainage of the entire region in a big rainstorm case, this shortfall was more pronounced. According to these pipes network specific condition, we can put forward the corresponding improvement plan in the actual network of transformation.

CONCLUSION

In this study, in the case of different frequency design storm drainage capacity of the regional pipeline network changes, provide a reference to the actual identification of the drainage capacity of the pipe network. The study found that the regional network design storm in return period is small, can satisfy the drainage requirements, but when the rain gets large return period, especially when P increased to 5 or 10 a, the network has 57.4% of the pipeline full flow over a long period of time, which cause the rain overflow, produce the submerged. Combined with the actual required drainage requirement, Statistical problems in charge of this network, we can make targeted to improve the program. At the same time, based on the powerful drainage system simulation function of SWMM model, the model can also be used for improvement and assessment of city drainage system planning program and can provide strong technical support for the city drainage system planning and management.

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REFERENCES

- Keifer, C.J. and H.H. Chu, 1957. Synthetic storm pattern for drainage design. *ASCE J. Hydraulics Division*, 83(HY4): 1-25.
- Liu, J. and X. Xu, 2001. City storm model in Tianjin urban drainage analysis calculation. *Hehai Water*, 1: 9-11.
- Parka, S.Y., K.W. Leeb, I.H. Parkb and S.R. Ha, 2008. Effect of the aggregation level of surface runoff fields and sewer network for a SWMM simulation. *Desalination*, 226: 328-337.
- Rui, X., 2004. *Hydrology Principle*. Water Power Press, Beijing, China.
- Tang, G. and X. Yang, 2006. *ArcGIS Geographic Information System Spatial Analysis Experimental Course*. Science Press, Beijing, China.
- Wang, X. and Z. Xu, 2008. Study on simulation model of city rain water flood development. *Proceeding of Conference on China Water Conservancy Society*, China Water Power Press, Beijing, 2: 931-939.
- Xu, Z., 2009. *Hydrological Model*. Science Press, Beijing, China.