Evaluation of the Structure of Urban Stormwater Pipe Network Using Drainage Density

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Abstract: In mega cities such as Seoul in South Korea, it is very important to protect the city from the flooding even for the short time of period due to the enormous amount of economic damage. In impervious area of the city, stormwater pipe network is commonly applied to discharge rainfall to the outside of catchment. Therefore, the stormwater pipe network in urban catchment should be carefully designed to discharge the runoff quickly and efficiently. In this study, different types of structures in stormwater pipe network were evaluated using the relationship between the peaks rainfall and runoff in urban catchments in South Korea. More than 400 historical rainfall events were applied in five urban catchments to estimate peak runoff from different type of network structures. Linear regression analysis was implemented to estimate peak runoffs. The coefficient of determination of the regressions were higher than 0.9 which means the regression model represent very well the relationship between the two peaks. However, the variation of the prediction becomes large as the peak rainfall increases and the variation become even larger when the network structure is branched. Therefore, it depends on the structure of stormwater pipe network. When the water paths in the pipe network is unique (branched network), the increased amount of rainfall is congested around the rainwater inlets and the uncertainty of peak runoff prediction is increased. If there are many possible water paths depending on the amount of discharge (looped network), the increased rainfall is discharged more quickly through the many water paths. This can be a way to represent the reliability of the stormwater pipe network. The structures of stormwater pipe network is evaluated using drainage density which is the length of pipes over the unit catchment area and 95% confidence interval. As a result, the 95% confidence interval is increased as the drainage density is increased because the accuracy of peak runoff prediction is decreased. As mentioned earlier, because the looped networks have many alternative water flowing paths, elimination time of rainfall from the catchments become short, the 95% confidence interval become narrow, and the reliability of peak runoff prediction become high. Therefore, it is beneficial to install looped stormwater pipe network within the affordable budget. It is important factor to determine the amount of complexity in stormwater pipe network to decrease the risk of urban flooding.

Keywords: urban floods, stormwater pipe network, drainage density, flood risk

1. Introduction

Due to the recent climate change, the frequency of torrential rains has been increased in South Korea, particularly in the urban area. The torrential rains in urban area could cause temporal and local surface flooding due to the lack of discharge capacity. According to the 2010 disaster report,

torrential rains in Seoul caused 64,752 people injured and about 0.6 billion USD of property damage. As such, the flooding in the urban catchment could result in massive property damage and loss of human life. Therefore, it is important to analyze the accurate runoff and inundation calculation.

SWMM model is popularly applied to calculate runoff in urban catchment. However, it is impossible to simulate the natural phenomenon resulting from rainfall. Therefore, the uncertainty of urban runoff is commonly applied to the interpretation of the natural phenomenon for the reliable flow analysis. Ref. [3] calculated the uncertainty quantification index of the SWMM model parameters and based on the case in Beijing, China. Parameters in SWMM were optimized [16] using the GLUE method. Ref. [4] quantified the uncertainty of the model through repetitive simulations using a randomly selected set of parameters using Monte Carlo analysis. Ref. [13] also analyzed the uncertainty by applying the Meta-Gaussian technique to the simulated runoff from the HEC-HMS model.

There is also an uncertainty in rainfall data. Ref. [2] quantitatively assessed the impact on runoff using errors from rainfall observations. Ref. [14] examined the structured and unstructured uncertainty of rainfall. Ref. [5] noted that spatial variability of rainfall is one of the major causes of the uncertainty. Ref. [10] was used radar rainfall to estimate probability distribution for urban runoff.

The relationship between drainage density and runoff in the natural watershed is presented by [1] using 13 river basin data in the eastern United States. For the natural watersheds, Ref. [17] analyzed the impact of impervious areas and drainage density on the runoff. The effect of drainage density was the largest. In urban catchment, the stormwater pipe network is artificially constructed and the pipe network behaved in the natural rivers. Therefore, the characteristics of stormwater pipe network should be understood for the efficient design and mitigation of flooding. In this study, drainage density was applied in urban stormwater networks. The relationship between peak rainfall and peak runoff was analyzed to estimate the accurate runoff from the catchments.

2. Data collection

2.1. Weather data

Urban floods frequently caused by torrential rains would result the property damage and loss of life [13]. As of December 2003 in South Korea, there are 719 of frequently flooded areas which means flooding happens every year. According to [19], the main reasons of the frequent flooding in the city were the poor drainage systems. More specifically, the drainage pipes does not have enough capacity to discharge the torrential rains, thus the lowlands were inundated and runoff cannot be discharged to the drainage systems.

To analyze the flood characteristics and stormwater pipe networks, historical flood damage data in Seoul and Busan where are the two largest cities in South Korea were collected as shown in Table 1.

Table 1. Flooding damages in the study catchments during last 10 years (2004~2013)

District	Total amount of flooding damage ($)	Number of flooding years
Yeongdeungpo-gu (Seoul)	900,000	4
Guro-gu (Seoul)	870,000	6
Geumcheon-gu (Seoul)	900,000	4
Yeonje-gu (Busan)	3,580,000	5

* Data were acquired from Meteorological data link portal and WAMIS. (http://www.wamis.go.kr)

As mentioned, Seoul and Busan were the largest cities in South Korea and urbanized rate were very higher than other cities. There are a meteorological station in each city as shown in Fig. 1. Average annual rainfall during the rainy season (Jun. to Oct.) from 1975 to 2015 were slightly increasing.

(a)

(b)

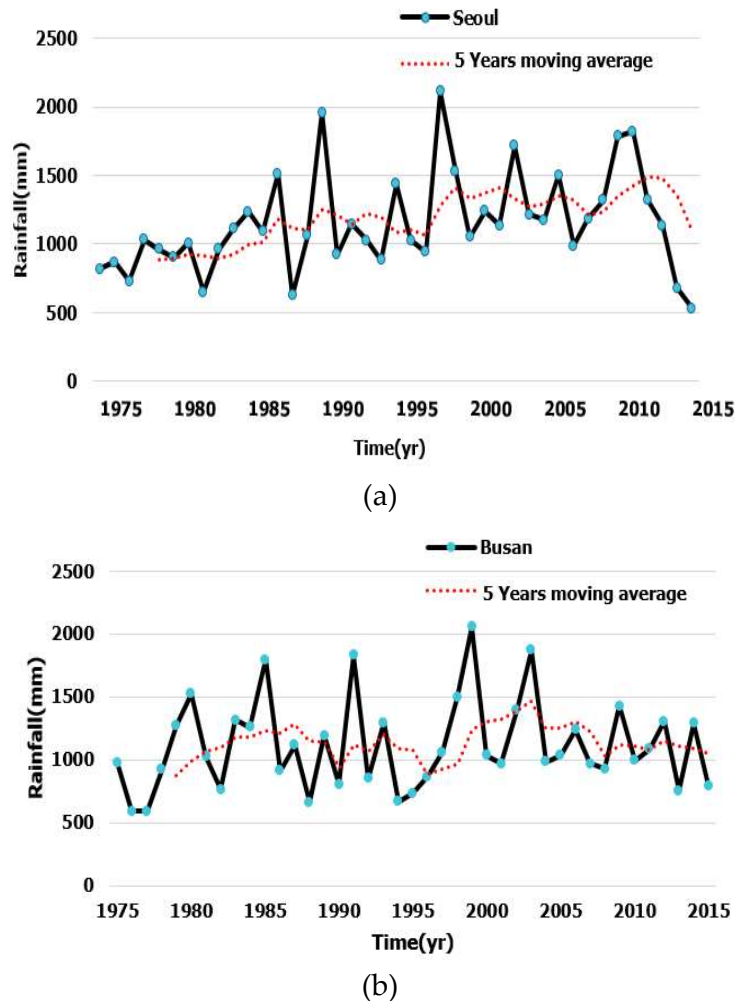
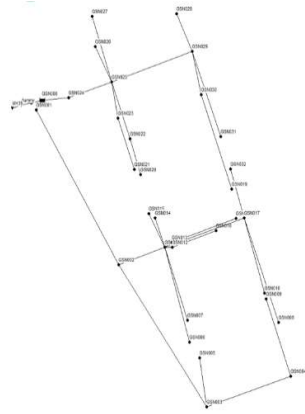



Figure 1. Annual rainfall during the rainy season (Jun.~Oct.) and moving average of meteorological stations in Seoul (a) and Busan (b)

2.2. Urban catchments

The five urban catchments in Seoul and Busan were selected as shown in Fig. 2. Number of subcatchments, number of nodes and links, catchment area, and total length of pipes were listed in Table 2. The structure of stormwater pipe networks were originally constructed using GIS files provided by stormwater pipe information systems in Seoul and Busan cities. The original structures were simplified using the method of [18]. As shown in Fig. 2, network A is the simplest network having loops and network B is the most complicated network with many loops. Networks C and E are the common styles of stormwater pipe networks in South Korea which is the combination of branched and looped networks. Network D is typical type of branched network.

(a) **Catchment A**

(b) **Catchment B**

(c) **Catchment C**

(d) **Catchment D**

(e) **Catchment E**

Figure 2. Structure of stormwater pipe networks in study catchments using SWMM

Table 2. Statistics of stormwater pipe networks in SWMM

Catchment	No. of Subcatchments	No. of Nodes	No. of Links	Area (ha)	Total pipe length (m)
A	32	35	35	48	5,219
B	1,643	1,881	2,053	248	59,976
C	620	620	632	892	37,586
D	196	196	236	5,724	29,134
E	451	512	526	355.8	20,120

3. Methods

3.1. EPA-SWMM

EPA-SWMM was developed in 1971 to estimate the flow and water quality caused by rainfall in urban areas. Runoff in SWMM was simulated from single or continuous rainfall and snowmelt [6]. The SWMM model was simulated by three types of analysis methods: steady state, kinematic wave, and dynamic wave methods. The kinematic wave method assumes that the friction gradient is the same as the slope gradient. Since the kinematic wave method has a large time interval, the long term is generally applied to the prediction. The dynamic wave method was applied in the unsteady flow to solve continuity and momentum equations. Also, the dynamic wave method is applied in the surface flow when the pipes were full with the rainfall [15].

The dynamic wave method uses the momentum equation in eq.(1).

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial y}{\partial x} + \frac{V}{\partial t}\,\overline{q} - g(S_0 - S_f) \tag{1}$$

In eq.(1), V is the average velocity of the flow, y is the depth of water, Sf is the slope or friction slope of the energy line, q is the lateral inflow, g is the gravitational acceleration, and So is the surface slope. The first term in the dynamic wave method was related to inertia force, the second term and the third term are the pressure, the fourth term is the momentum change, and the fifth term is related to gravity and frictional forces. To make the equation simple, the fourth term can be ignored. It is used to calculate flood wave movements in natural rivers, which are wide but not deep such as flood propagation downstream due to dam breaks.

3.2. Simple linear regression analysis

When observations are given in pairs, one variable is used to predict another variable. Linear regression analysis is a statistical analysis method that assumes that there is a linear relationship between two variables. The basic formula of the linear regression analysis is in eq.(2).

$$Y = \alpha + \beta x \tag{2}$$

Where, Y is the dependent variable, x is the independent variable, α is the Y intercept, and β is the regression coefficient. The coefficient of determination (R-squared) is a measure whether the proposed equation is appropriate to represent the data set. It is the percentage of the variable that can be explained by the proposed model. The coefficient of determination is defined by the eq.(3).

$$R^2 = \frac{SSR}{SST} \tag{3}$$

Where, SST is the Total Sum of Squares and SSR is Sum of Squares due to Regression. SST means how far the observed Y_i value is from the mean of the Y_i, and SSR means how far the estimate is from the mean. The range of the coefficient of determination is $0 \le R^2 \le 1$. The R^2 is closer to 1, the better the regression model explains the data.

3.3. Drainage density

Drainage Density is a numerical value indicating the degree of dense network in the watershed. High drainage density means that the length of stream per unit area is long, thus the drainage speed is relatively faster. Low drainage density means that the length of stream per unit area is short and the drainage speed is relatively slow.

4. Analysis and results

4.1. Peak runoff and Peak rainfall

In order to analyze the runoff from the urbanized catchments, the historical rainfall data are generally used and the rainfall data should be separated into rainfall events using such concepts as Inter-Event Time Definition (IETD). As recommended in [15], rainfall events were separated based on the 11 hours of IETD in every five catchments. Rainfall events were separated from the hourly-precipitation data observed in Seoul and Busan Korea Metropolitan Administration (KMA) from 1975 to 2015. Only total rainfall events in which total amount of rainfall is greater than 30 mm was selected for the runoff calculations. The number of rainfall events were 427 and 419 in Seoul and Busan, respectively.

The runoff was calculated using SWMM model, as mentioned previously. Dynamic wave method was used to consider the flow characteristics during surface flooding and the pressure effects due to inverse slope in some parts of catchments.

Regression analysis between the peak rainfall and runoff was implemented as listed in Table 3. The coefficient of determination (R^2) in all cases was 0.9 or higher. The regression graph were shown in Fig.3. It shows that the peak runoff increases almost linearly as the peak rainfall increases. However, when the peak rainfall is high, the variation of peak runoff is increased. Average widths of 95 % confidence intervals in the A, B, C, D and E basin were 0.6 ㎥/s, 0.3 ㎥/s, 2.56 ㎥/s, 20.8㎥/s and 1.6㎥/s. The catchments B has the smallest width of 95% confidence interval and highest R^2 which is close to 1. It means the accuracy of peak runoff prediction in catchment B is higher than other catchments. The catchment B has many loops and complicated network structure as shown in Fig. 2. Therefore, there are many alternative water flow paths when the peak rainfall is high and the peak runoff is discharged without delay through the various water flow paths.

In contrast, catchment D has the largest width of 95% confidence interval and the smallest R^2. As shown in Fig. 2, stormwtaer pipe networks in catchment D is branched pipe network structure which has the unique water flow path. When the rainfall intensity and peak rainfall are increased, the capacity of stormwater pipes was exceeded and the surface flooding could be happened locally. After the short time period of flooding, the exceeded runoff is discharged through the stormwater pipes as well, however, the surface flooding might cause property damage already.

Catchments C and E are also branched networks, however, the average width of 95% confidence intervals are smaller than catchment D. This is because the catchment area of C and E are much smaller than catchment D. Therefore, it is expected that the catchment area and the length of water flow paths plays an important role to estimate the accurate peak runoff. The short travel time of catchments C and E decreases the uncertainty of the peak runoff prediction and increases the reliability.

Table 3. Results of regression analysis between peak rainfall and peak runoff in urban catchments

Catchment	Regression equation	R^2	Average width of 95% confidence interval (m/s)
A	y = 0.1182x - 0.2834	0.9787	0.6
B	y = 0.6554x - 0.907	0.9969	0.3
C	y = 1.4049x - 3.0924	0.9522	2.6
D	y = 9.7278x - 34.355	0.9079	20.8
E	y = 1.0245x - 2.2035	0.9610	1.6

(a) **Catchment A**   (b) **Catchment B**

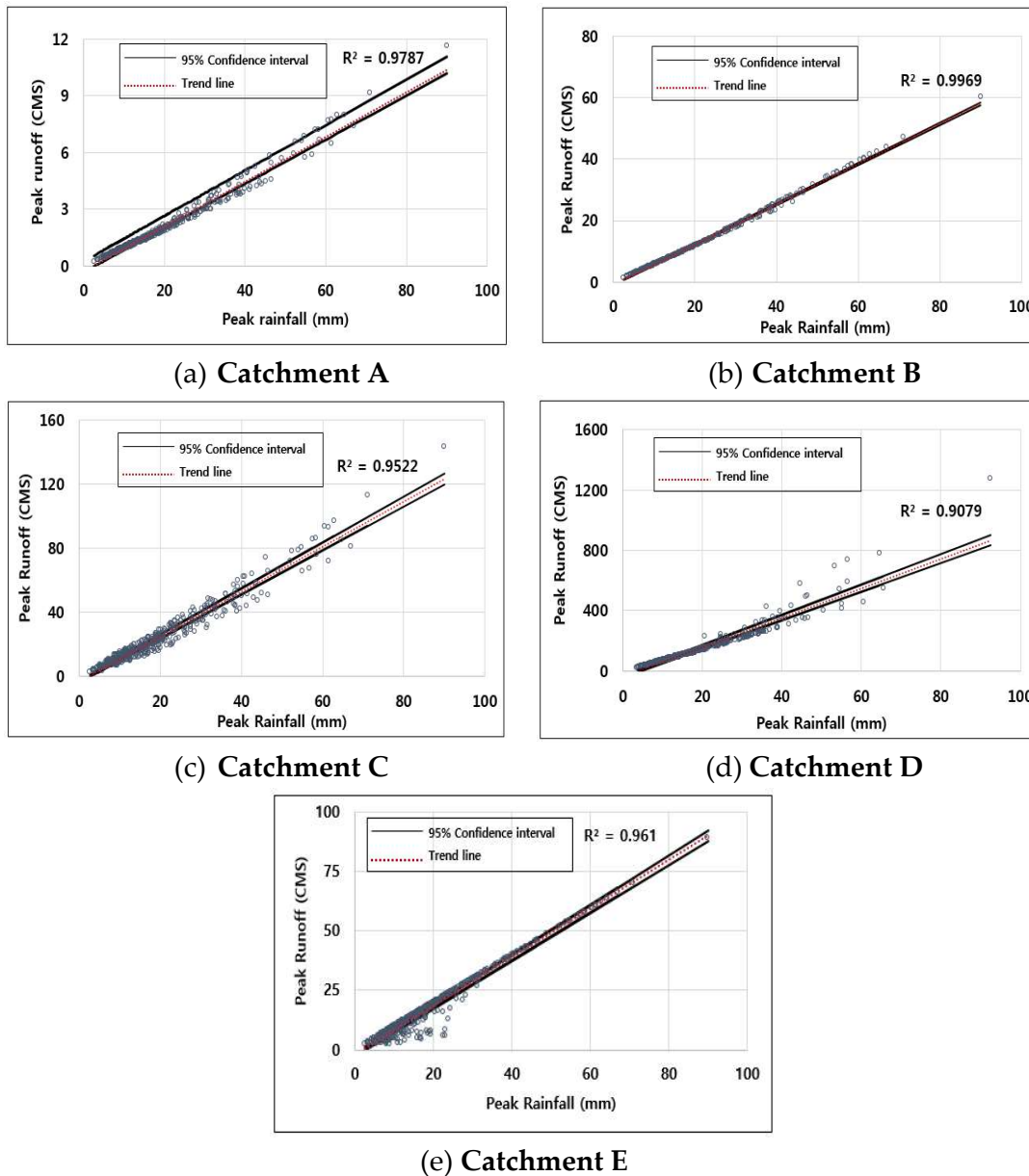
(c) **Catchment C**   (d) **Catchment D**

(e) **Catchment E**

Fig 3. Regression analysis between peak rainfall and runoff in urban catchments

4.2. Drainage density analysis

As mentioned earlier, the catchment area and length of water flow path are important to predict the peak runoff. Therefore, drainage density of the study catchments were calculated as listed in Table 4. The drainage density of A, B, C, D and E catchments are 107.7 ha/m, 241.3 ha/m, 42.1 ha/m, 5.1 ha/m and 1.6 ha/m. Catchment B has the highest drainage density and R^2 and the lowest average width of 95 % confidence interval and coefficient of variation. As mentioned previously, the catchment B has the complicated looped pipe network structure and easier to estimate the accurate peak runoff when the peak rainfall is increased due to the various water flow paths. It means that catchment B discharge the rainfall the most efficiently among the study catchments.

In the other hand, catchment D has the lowest drainage density and R^2 and the highest average width of 95% of confidence interval and coefficient of variation. Therefore, the pipe density over the catchment is low and the runoff could be discharged inefficiently due to the lack of

capacity of pipes. This can cause surface flooding for the short time of period and make the travel time longer.

Table 4. Results of drainage density calculation

Watersheds	Drainage density(m/ha)	R^2	Average width of 95% confidence interval (m/s)	Coefficient of variation
A	107.7	0.9787	0.6	77.8
B	241.3	0.9969	0.3	72.7
C	42.1	0.9522	2.6	80.0
D	5.1	0.9079	20.8	85.6
E	56.5	0.9610	1.6	77.4

Fig. 4 shows a change of average width of 95 % confidence interval and R^2 depending on drainage density. As shown in Fig. 4, as the drainage density increases, average width of the 95 % confidence interval decreases and R^2 increases. This means that the uncertainty of the prediction of peak runoff is increased as the drainage density is decreased.

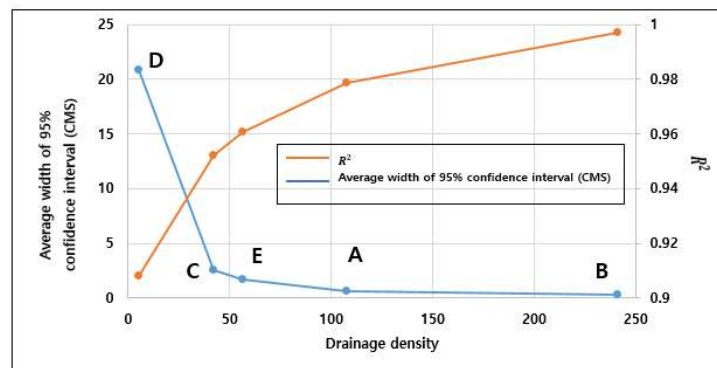



Fig. 4. Changes of R^2 and 95% confidence interval depending on drainage density

5. Conclusion

In mega cities such as Seoul in South Korea, urban floods causes enormous amount of economic damage. In impervious area of the city, stormwater pipe network is commonly applied to discharge rainfall to the outside of catchment. However, the inundation is occurred around the rainwater inlets due to the lack of pipe capacity when the rainfall intensity is higher than design capacity. The inundation is usually diminished after the short period of time, however, the property damage could be not small. In this study, the structures of stormwater pipe network were evaluated using the relationship between the peaks rainfall and runoff in urban catchments of Seoul and Busan in South Korea. Historical 41 years of rainfall data from 1975 to 2015 and more than 400 rainfall events were applied in five urban catchments. Linear regression analysis was implemented to estimate peak runoffs from different peak rainfalls. The coefficient of determination of the regressions were higher than 0.9 which means the regression model represent very well the relationship between the two peaks. However, the variation of the prediction becomes large as the peak rainfall increases. It depends on the structure of stormwater pipe network. When the water paths in the pipe network is unique (branched network), the increased amount of rainfall is congested around the rainwater

inlets and the uncertainty of peak runoff prediction is increased. If there are many possible water paths depending on the amount of discharge (looped network), the increased rainfall is discharged through the many water paths in the relatively shorter time. This can be a way to represent the reliability of the stormwater pipe network. The structures of stormwater pipe network is evaluated using drainage density which is the length of pipes over the unit catchment area and 95% confidence interval. As a result, the 95% confidence interval is increased as the drainage density is increased because the accuracy of peak runoff prediction is decreased. As mentioned earlier, because the looped networks have many alternative water flowing paths, elimination time of rainfall from the catchments become short, the 95% confidence interval become narrow, and the reliability of peak runoff prediction become high. Therefore, it is beneficial to install looped stormwater pipe network within the affordable budget. It is important factor to determine the amount of complexity in stormwater pipe network to decrease the risk of urban flooding.

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References

1. Carlston, C.W. Drainage density and streamflow. U.S.G.S. Professional Paper 1964, 422-C, 1–8.
2. Choi, K.S.; Kyoung, M.S.; Kim, H.S.; Kim, B.S. Evaluation of effects of rainfall errors on Discharge, The 33rd Annual Meeting of the Korean Society of Civil Engineers CIVIL EXPO 2007, 1958-1961.
3. Chung, G.H.; Sim, K.B.; Kim, E.S. Uncertainty Quantification Index of SWMM Model Parameters 2015, Journal of Korea Water Resources Association, 48-2, 105-114. [DOI : http://dx.doi.org/10.3741/JKWRA.2015.48.2.105]
4. Enrique, M.; Pedro, T.; Gabriel, O. Uncertainty in rainfall input data in a conceptual water balance model: effects on outputs and implications for predictability 2014, Earth Sciences Research Journal, 18, 1. [DOI: https://doi.org/10.15446/esrj.v18n1.38760]
5. Hilary, M.; Bethanna, J.; Martyn, C.; Dmitri, K.; Ross, W. Rainfall uncertainty in hydrological modelling: An evaluation of multiplicative error models 2011, Journal of Hydrology, 400, 83-94. [https://doi.org/10.1016/j.jhydrol.2011.01.026]
6. Hong, J. B. Assessment of Food Flow Conveyance for Urban Stream Using XP-SWMM. Master's Thesis, Inha University, 2005, Incheon, Republic of Korea.
7. Jang, H. C. (a) Basic and Detailed Design for Improvement of Rainwater Pump Station Facilities (Expansion 1 Area) Gasan 1 Rainwater Pump Station Report 2009, Seoul: River management section.
8. Jang. H. C. (b) Basic and Detailed Design for Improvement of Rainwater Pump Station Facilities (Expansion 3 Area) Gaebong 1 Rainwater Pump Station 2009, Seoul: River management section.
9. Jang, H. C. Basic and Detailed Design for Improvement of Rainwater Pump Station Facilities (Extension 3 Area) Daerim 3 Rainwater Pump Station 2009, Seoul: River management section.
10. Kang, N.; Joo, H.; Lee, M.; Kim, H.S. Generation of radar rainfall ensemble using probabilistic approach, *Journal of Korea Water Resources Association* **2017,** 50,155-167. [DOI : 10.3741/JKWRA.2017.50.3.155]
11. Kang, S.H.; Heo, W.M.; Kang, S.H. Water Balance Estimate of LID Technique for Circulating Urban Design, *Journal of Environmental Science International* **2015**, 24, 1065-1073. [DOI : 10.5322/JESI.2015.24.8.1065]
12. Kim, B.S.; Kim, B.K.; Kwon, H.H. Evaluation of the Uncertainties in Rainfall-Runoff Model Using Meta-Gaussian Approach, *Journal of Korean Wetlands Society* **2009**, 11, 49-64.
13. Kim, E.S.; Yoo, J.Y.; Chung, G., Park, M.J.; Choi, H.I. Analysis of the Disaster Environmental Change Considering Climate Change : 2. Flood Risk Area Assessment, *Journal of the Korean Society of Hazard Mitigation* **2013**, 13, 219-226. [DOI: 10.9798/KOSHAM.2013.13.4.207]
14. Lee, H.; Jeon, M.W.; Balin, D.; Rode, M. Application of Rainfall Runoff Model with Rainfall Uncertainty, *Journal of Korea Water Resources Association* **2009**, 42, 773-783. [DOI : 10.3741/JKWRA.2009.42.10.773]

15. Lee, J. Estimation of InterEvent Time Definition Using in Urban Areas, *Journal of Korean Society of Hazard Mitigation* **2017**, 17, 287-294. [DOI : 10.9798/KOSHAM.2017.17.4.287]

16. Li, M.; Yang, X.; Sun, B.; Chen, L.; Shen, Z. Parameter Uncertainty Analysis of SWMM Based on the Method of GLUE, *2016 7th International Conference on Biology*, Environment and Chemistry, 98. [DOI: 10.7763/IPCBEE. 2016. V98. 11]

17. Ogden, F.L. Pradhan; N.R., Downer; C.W.; Zahner, J.A Relative importance of impervious area, drainage density, width function, and subsurface storm drainage on flood runoff from an urbanized catchment, *Water Resources Research* **2011**, 47, W12503. [10.1029/2011WR010550]

18. Park, J.; Lee, S.; Lee, B. Development of Storm Sewer-Network Extraction Tool(SS-NET) for Creating Pipe Network Input Data of Urban Rainfall-Runoff Model, *Journal of Korean Society of Hazard Mitigation* **2017**, 17, 79-86. [DOI : https://doi.org/10.9798/KOSHAM.2017.17.1.79]

19. Shim, U.B. Characteristics of the flood damage in Korea and the corresponding task, *Journal of Korea Water Resources Association* **2008**, 41, 41-46.

20. Shon, T.S.; Kang, D.H.; Jang, J.K.; Shin, H.S. A study of Assessment for Internal Inundation Vulnerability in Urban Area using SWMM, *Journal of the Korean Society of Hazard Mitigation* **2010,** 10, 105-117.

21. KMA, Meteorological data link portal, https://data.kma.go.kr/cmmn/main.do, (accessed July 30, 2017)

22. WAMIS, http://www.wamis.go.kr, (accessed July 30, 2017)