

Sensitivity of urban drainage networks to spatio-temporal rainfall variability: A case study in Seoul, South Korea

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1. Instruction

Prediction of runoff hydrographs has been being a long-standing topic of hydrology. It is well recognized that the surface runoff from a watershed depends on the hydro-meteorological characteristics of the rainfall and the physiographic properties of the watershed (Yen and Chow, 1969). Physiographic properties includes watershed properties including area, slope, geometry and land use of a watershed and drainage network properties. Physiographic properties can be divided into surface and subsurface features. Infiltration and antecedent conditions can also be regarded as additional factors affecting a flow hydrograph (Singh, 1997). The temporal and spatial rainfall variation caused by the rainstorm movement, which results in significant difference in hydrologic response at the outlet of a watershed for a given amount of rainfall.

This research involves understanding how spatio-temporal rainfall variation affects the hydrologic response of a catchments, particularly in urbanized areas. The focus this research is on the relation between rainfall variation and network configuration, which is one of the characteristics of a catchment. The Gibbsian model is introduced to represent the property of a network. One-parameter Gibbs' model is a stochastic network model suggested by Troutman and Karlinger (1992). It covers uniform model (Karlinger and Troutman, 1989) and the Scheidegger model (Scheidegger, 1967). 31 catchments in Seoul, South Korea were examined to investigate the applicability of the Gibbsian model to urban drainage networks and difference from natural river networks. In addition, observed rainfall and flow data were used to evaluate the relation between sensitivity of urban drainage networks and spatio-temporal rainfall variability depending on network configuration.

2. Methods

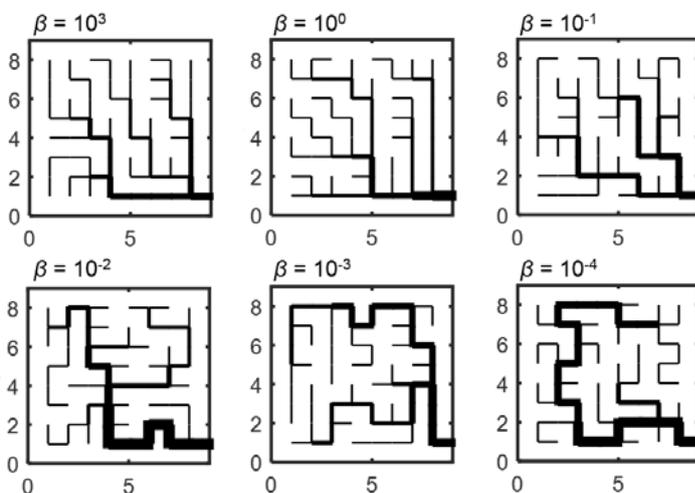


Figure 1. Dendritic networks generated by Gibb's model on a 8×8 lattice. The sinuosity of the network depends on the parameter value β .

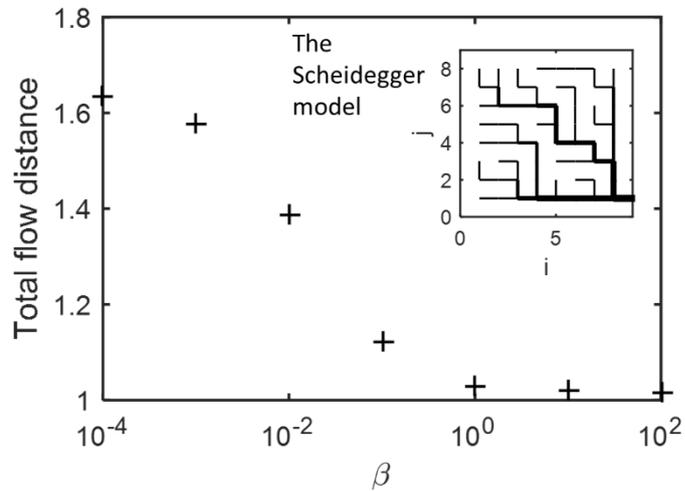


Figure 2. Total flow distance represents the sum of total distance from the outlet divided by that of the Scheidegger model, which has the shortest distance from the outlet. For example, Gibb's model with $\beta = 10^{-2}$ has about 1.4 times longer distance compared to the Scheidegger model. The flow distance was averaged from 100 simulations of Gibbs' model for each β .

We adopted the Gibbsian model. The parameter value of the Gibbsian model represents the overall sinuosity of the network. As the parameter value (β) increases, the network becomes less sinuous and vice versa as shown in Figure 1. The sinuosity can be defined as the total sum of distance from the outlet for each point subtracted by the total sum of the shortest distance from the outlet for each point. The Scheidegger model can be utilized to represent the shortest distance from the outlet because the Scheidegger model has downstream flow direction only (Figure 2). As beta increases the flow distance is close to 1 whereas the flow distance increases up to 1.62 for Gibbs' model with β equal to 10^{-4} .

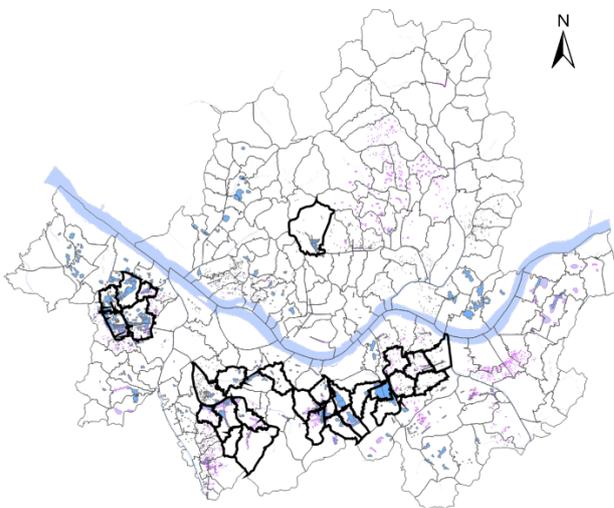


Figure 3. The metropolitan city of Seoul is composed of 238 subcatchments. Black-lined watersheds

with areas from 0.32 to 8.37 square kilometers are selected to estimate the value of β . The shaded area also shows the flooded areas caused by flash storms in 2010 and 2011. In particular, the damages in 2010 were concentrated on the south-eastern area (Shinweol) of Seoul, where the local drainage network mainly flows eastward whereas the westerlies dominate the storm direction.

First, we analyzed the network characteristics of 31 drainage networks of Metropolitan City of Seoul, South Korea. Areas of catchments considered in this study range from 0.51 to 8.59 square kilometers. The procedure used in this study in order to generate the Gibbsian model given a parameter, β is as follows: First, start from a network, s_1 generated by the Uniform model and randomly select a point, v in the network and assign a new flow direction from v to generate adjacent network s_2 . Second, check whether the new network, s_2 is acyclic. If not, repeat the first step. Third, draw a random probability x between zero and one and check that x is greater than $\exp(-\beta[\Delta H])$ where H is sinuosity, ΔH is equal to $H(s_2) - H(s_1)$. If this holds, then take s_2 as a new network. In the next step use s_2 as the starting network and repeat these steps sufficiently number of times that the resulting tree has the distribution close to the stationary Gibbs' distribution. In order to obtain the network configuration of drainage networks, 100 networks for each parameter value were generated for a catchment. Comparing the average width function from the simulation, the representative parameter value of the corresponding catchment was obtained.

Second, rainfall and flow data were collected for the period of 2011-13 to evaluate the relation between sensitivity of urban drainage networks and spatio-temporal rainfall variability depending on network configuration.

3. Results and discussion

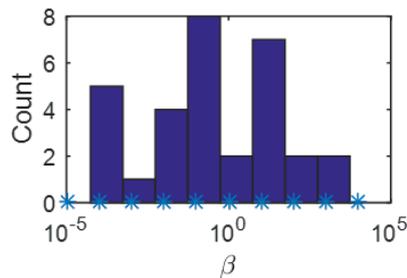


Figure 4. Distribution of β for 31 catchments in Seoul. The result shows that Seoul has a wide range of drainage network configuration from β equal to 10^{-4} to 10^3 .

As shown in Figure 1, a network with smaller beta is more sinuous and longer flow distances. In contrast, a network with larger beta is less sinuous and shorter flow distances. In terms of drainage time, a network with smaller beta is inefficient whereas it is efficient with larger beta. One of the key findings of this study is that the network configuration of urban drainage network is not much efficient compared to river in Nature. Especially, compared with the results from Troutman and Karlinger (1992), some of the drainage networks in Seoul are less efficient than river in nature (beta of 10^0). This is contrary to typical common sense that a man-made drainage system is efficient in terms of drainage time mainly due to decreased roughness in artificial drainage systems. However, in terms of overall network configuration, the results of this study show that man-made drainage systems can be less efficient than river in nature. This is consistent with the results from Seo and Schmidt (2012).

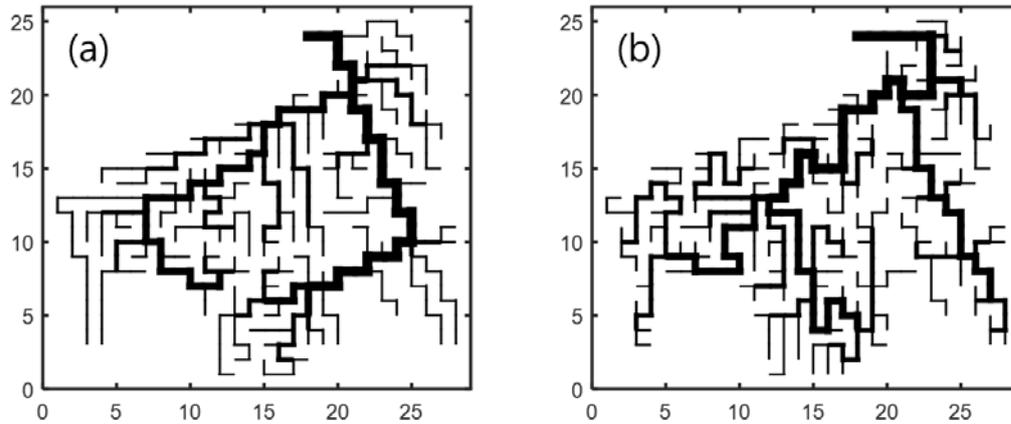


Figure 5. (a) Actual drainage network of a catchment (Seocho4) reconstructed on a lattice and (b) Gibbs' model with beta equal to 10^{-2} simulated on the same boundary and outlet. The original drainage network has beta of 10^0 . Same diameter and slope of conduit were used to build SWMM from Gibbs' model depending on Strahler order.

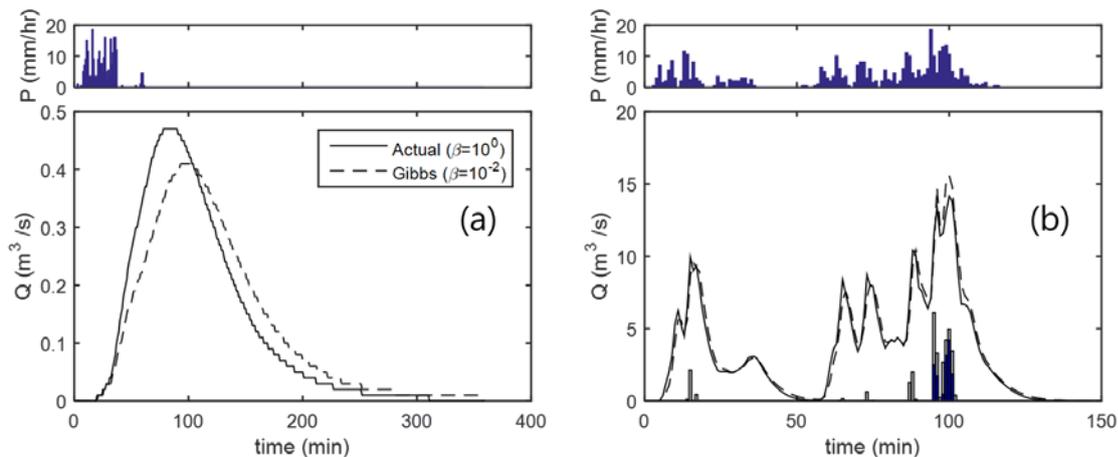


Figure 6. Hydrographs of Seocho4 for the events of (a) September 14, 2011 (no flooding) and (b) August 7, 2010 (flooding) obtained using SWMM. The solid line is a hydrograph from the actual drainage network of Seocho4 and the dash is that from Gibbs' model with beta is equal to 10^{-2} . The bar graphs in the lower figure of (b) is flooding. The white bar is flooding from the actual network, black one is from the Gibbs' model. Figure (a) shows that network configuration in terms of layout affect the hydrographs at the outlet. Figure (b) shows that the hydrographs from two networks are quite similar. Even, the peak from Gibbs' model is higher around after 100 minutes. However, the flooding amount is much higher for the original drainage network.

The results of this study also that more efficient (less sinuous) drainage network is more sensitive to spatio-temporal rainfall variability than less efficient (more sinuous) drainage network. The observation from 2012 to 2013 shows that more efficient networks showed higher peaks compared to less efficient networks. This is important in that it implies a network configuration which is both efficient and less sensitive to spatio-temporal rainfall variation. It implies an optimum network

configuration which potentially mitigate flood risks in urban environments.

4. Conclusion

The analysis showed that the network configuration of urban drainage networks can be wider compared to river networks, which is counter-intuitive because artificial drainage networks were thought to be efficient. Moreover, this study shows that an efficient drainage network in terms of drainage time is much more sensitive to rainstorm movement in terms of peak flows compared to less efficient or highly sinuous drainage networks. As a consequence, peak flows of a drainage network are higher and the corresponding catchment becomes more sensitive to temporal and spatial variation of rainfall as the network is efficiently organized further and further. This is a paradox between efficiency and safety of urban drainage networks. Depending on dominant storm kinematics and flow direction of a catchment, the network configuration can be an important factor affecting the safety of the catchment from flood risks. The preliminary result shows the layout of urban drainage networks is crucial and a compromise between network efficiency and the security of urban catchments from flood risks is required. In this regard, this study suggests the need to consider network configuration as one of the alternative nonstructural measures to mitigate the flood risks in urban environments.

Acknowledgements

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