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THE IMPACT OF SPATIAL DISCRETIZATION SCALE ON URBAN HYDROLOGICAL MODELING PERFORMANCE AND PREDICTION

QING CHANG[1], SO KAZAMA[2] & YOSHIYA TOUGE[3]

[1,2,3] Graduate School of Engineering, Tohoku University, Sendai, Japan.
qing.chang.q3@gmail.com; so.kazama.d3@tohoku.ac.jp; yoshiya.touge.a6@tohoku.ac.jp

ABSTRACT

Urban catchments typically have high spatial variability and fast runoff processes which resulting in short response times. Thus distributed models are widely used in urban hydrology due to the capability to better capture the spatial heterogeneity. Selecting the proper spatial resolution (i.e., degree of aggregation) is not a trivial issue because this will affect the model output. However, a general consensus about the effect does not exist. This study investigated the impact of model input resolution on the outputs of detailed hydrodynamic models of an urban catchments in Sendai City of Japan. The aim is trying to quantify the impact of spatial resolution on model results and calibrated model parameters. Firstly a high resolution model was build up and calibrated. Based on this, a series of model was built via an upscale approach. The performances of these models were compared and afterward each model was calibrated independently. The parameterization and prediction capacities were discussed during and after the calibration. Finally, the runoff of an adjacent small catchment were modeled to analyze the model fidelity of performance and prediction at local scale. There were obvious scale effects across models due to the non-linearity nature of model structure. The peak flow tended to decrease with the upscale process while the total flow generally keep constant. Independent calibration had endowed all the models satisfied performance during the calibration period which indicated that calibration could completely compensate models' scale effect. However, the deterioration during the validation suggested a result of missing certain spatial information.

Keywords: Urban hydrological model; SWMM; scale analysis; parameters.

1 INTRODUCTION

Urban hydrological modeling is an important component of water resource management which include the design of drainage pipes and the assessment of land use change impacts. The large proportion of impervious area of urban catchment, as well as the man-made structures like roofs, roads and channels largely impacted overland flow and runoff routing process (Salvadore et al., 2015). Thus it is essential to make an accurate representation or characterization of urbanized catchment for hydrological modeling. The distributed urban hydrological models require different kind of the input data with different spatial scales such as precipitation, the drainage network, and parameter that representing various processes like the saturated hydraulic conductivity of the Green-Ampt infiltration model and Manning's roughness value for overland flow. These values typically vary spatially and can be captured by representing them with several smaller units, a process called model subdivision. The problem of model dispersion is one of the most common problems faced in the modeling process. When using hydrological models for simulation, the entire area will be divided into several hydraulic similar units (sub-catchments). Since the model is simulated calculated on the level of sub-catchments, so the degree of delineation will have an important impact on the output of the model.

In recent 10 years, the computational capacity and availability of high resolution distributed data have increased in a large degree. As a consequence, more and more researchers built up their model in high resolutions and using detailed methods. Recently, high resolution input data as well as multiple information source and urban features identification have already been used in flood modeling of urban area (Chang et al., 2018; Jang et al., 2018; Noh et al., 2018). Although it is an irreversible trend to model urban hydrology at higher resolution and in more detailed method, the benefit and drawbacks of doing so should be further discussed. One of the concerns is that the high resolution may lead to the increase of uncertainty or over-parameterization (Petrucci and Bonhomme, 2014). The other concern is the existence of effective parameters. These effective parameters can representing a global hydrological behavior, and some of them cannot be directly measured or linked to geographical data. This means that some low resolution models can have same performances with more detailed model and the former could save more resources. Therefore, the scale issue of distributed model should be considered more carefully.

In this study, the parameter and performance of models with different spatial discretization scales were discussed. A highly urbanized residential catchment were used as the study area. The EPA Storm Water Manage Model (SWMM) was used as the hydrological model for this study. This model is suitable for urban hydrology analysis and had been successfully applied at various scales.

2 METHODOLOGY

2.1 Study area

We chose the Kunimigaoka Area in Sendai City, Japan for the case study (Figure 1). KA is located in the north-western part of the uptown of Sendai City, which covers approximately 46 hector with a medium gradient slope topography. KA is featured with a temperate monsoon climate and the annual average rainfall and temperature are 1254 mm and 12.4C, respectively. KA is an old uptown where urbanization degree is rather complete and the land use shows little change after 2000. The urban land use accounts for over 90% of the total in this region. The storm water is firstly drained to a regulating pond and then to a downstream river. The drainage system of KA can be divided into two parts, one being the sewer network in the Northern part of KA which accounted for most of the drainage areas (around 41 ha); the other is a located in the southern part beside the regulating pond (around 5.1 ha). The outlets of the 2 drainage areas are marked in Figure1.

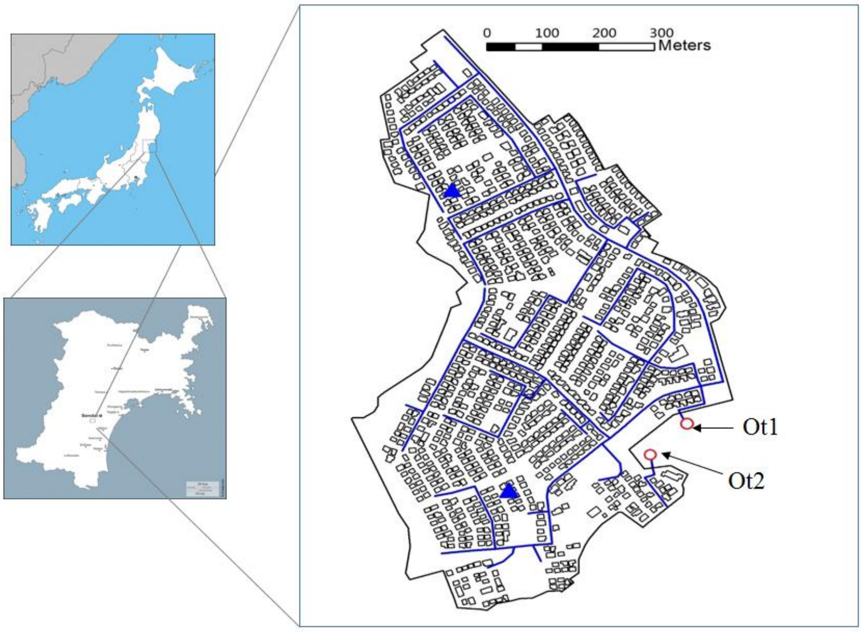

Figure 1. Location of the studied watershed in the City of Sendai. Drainage pipes (blue lines), rain gauge (blue triangle), outlet (red circle).

2.2 Data collection and preparation

2.2.1 Topographic data

The DEM of KA was available in the form of a high-resolution (5x5m) elevation data set, which was provided and quality controlled by the Land and Resources Department of Japan. In order to represent the blockage effect of buildings on surface flows, the building profiles were distinguished using the planar graph and Google satellite image.

2.2.2 Sewer network data

The underground pipeline data were obtained from Sewer Administration Office of Sendai City which contained geographic and geometric information of more than 400 pipelines and manholes. Most of the pipes were circular with diameters ranging from 0.3 to 2.4 m, while some pipes were rectangular whose widths and heights varied from 0.4 to 0.8 m. The pipe slopes showed a wide range, varying from 0.5 to 38%.

2.2.3 Rainfall and runoff data

The rainfall was collected by two tipping-bucket rain gauges within the catchment from February to July of 2018 and include 22 individual events. The record resolution of the rain gauge is 0.5 mm. These rainfall data were used for model calibration and validation. All those rainfall data were used for simulation to observe the scale effect of model.

At the outlet, the water level was recorded at 5 min intervals. The water level–flow rate relationship was obtained from a several velocity measurement campaign. There are some very small dry weather flow rate which could be originated from ground water exfiltration. Those flow was subtracted from records in order to obtain the storm water flow rate. Continuous measurements used for this study cover the period from 26th February 2018 to 29th July 2018

2.3 Model development and analysis

Table.1 characteristics of 4 models with different level of detail.

Model	Sub-catchment number	Average sub-catchment area (m2)	Modeled conduits	Total conduits length (m)
S1	3216	143.4	All Pipes and street gutters	18331.1
S2	147	3138.1	All pipes	6400.9
S3	26	17742.2	Partial pipes	3642.3
S4	6	76883.3	Partial pipes	1033.8

The models of the study area were build up at 4 levels of spatial resolution (S1, S2, S3, and S4). S1 model has the highest resolution and it is discretized based on urban structures like single roof top, a single garden or a short part of road. The sub-catchment of S2 model is divided based on the single urban blocks of the area. S3 is a transitional scale between S2 and S4 and is achieved by aggregating adjacent sub-catchments of S2 model according to drainage direction.S4 model is delineated based on the partition information of the drainage network. The summary of these 4 levels of models is listed in Table.1. After the model is set up, a sensitivity analysis is conducted. Several parameters are discussed: the impervious ratio (%imp), the depression storage depth on impervious and pervious areas (D-imp and D-perv), manning's roughness of overland flow (N-imp and N-perv) and conduit flow (N-cond), and the hydraulic conductivity (hc). The parameters sensitivities were calculated using a local one-at-a-time method:

$$S = \sum_{i=0}^{n-1} \frac{(Y_{i+1} - Y_i)/Y_0}{(P_{i+1} - P_i)/100} / n \qquad [1]$$

Where: S: Sensitivity value

Y_i: Model output of the i th run.

Y_0: Model output of initial parameter values.

P_i: Variation degree of a certain parameter in the i th run.

n: times of model run.

Here, the fluctuation range of parameters were set to [70%, 130%] with a step of 5%.

The model was optimized by using an automatic calibration method based on genetic algorithms. In recent years, automatic calibration methods have been widely used in the optimization of hydrological modeling (Mancipe-Munoz et al., 2014). In this study, the monitored rainfall runoff data were divided into the calibration period and validation period. The Nash–Sutcliffe efficiency (NSE) was selected as the objective function for the optimization:

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_m^t - Q_o^t)^2}{\sum_{t=1}^{T}(Q_o^t - \bar{Q}_o)^2} \qquad [2]$$

Where $\bar{Q}_o$ is the mean of observed discharges, and Q_m^t is modeled discharge while Q_o^t is observed discharge at time t. The closer to one (1) the NSE value, the better the efficiency of the model.

3 RESULTS AND DISCUSSIONS

3.1 Sensitivity analysis results

The results of global and local sensitivity analysis are shown in Figure 2. The sensitivity analysis have identified the most and least important parameters in the model. Overall, the parameters behave similarly in with different model resolution, with the most and the least important parameters fairly consistent across scenarios. Imperviousness is the most sensitive parameter, and its sensitivity is much larger than other parameters. The secondary important parameters are N-imp (Manning's roughness of impervious area) and N-con (Manning's roughness of conduits). Relatively, infiltration parameters, the hydraulic conductivity are not sensitive. The ranking of sensitive parameters are almost similar. This suggests that parameter sensitivities are not highly dependent on the grid size.

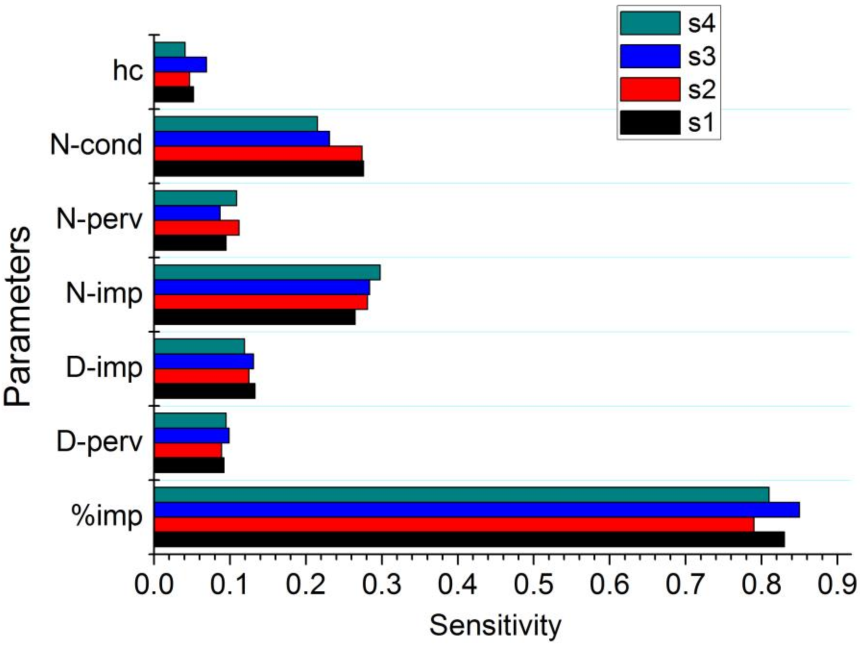

Figure 2. Parameter sensitivity results of models with spatial discretization

3.2 The scale effects and calibration of models

Firstly, only the S1 model was calibrated. The model showed satisfied performance for both calibration period (NSE=0.841) and validation period (NSE=0.744). Then those calibrated parameter sets were adopted in the S2, S3 and S4 models using areal weighted average method. All these model with different resolutions were run under all the 22 rainfall events. In order to compare the results of all the rainfall events, the general trends observed in the hydrologic outputs should be identified. The S1 model with the highest resolution was used as reference model. Hydrological modelling outputs were analyzed based upon these statistics: relative peak flows and relative total flows. The peak flows and total flows were normalized to those results of the S1 model.

Fig.3 has generalized the results of all the rainfall events simulated. It can be seen from the figure that as the spatial scale of the model decreased, the total flow and peak flow tended to decrease as well. While the variations of total flow were very slight, and the peak flows of different resolution showed a distinct variation.

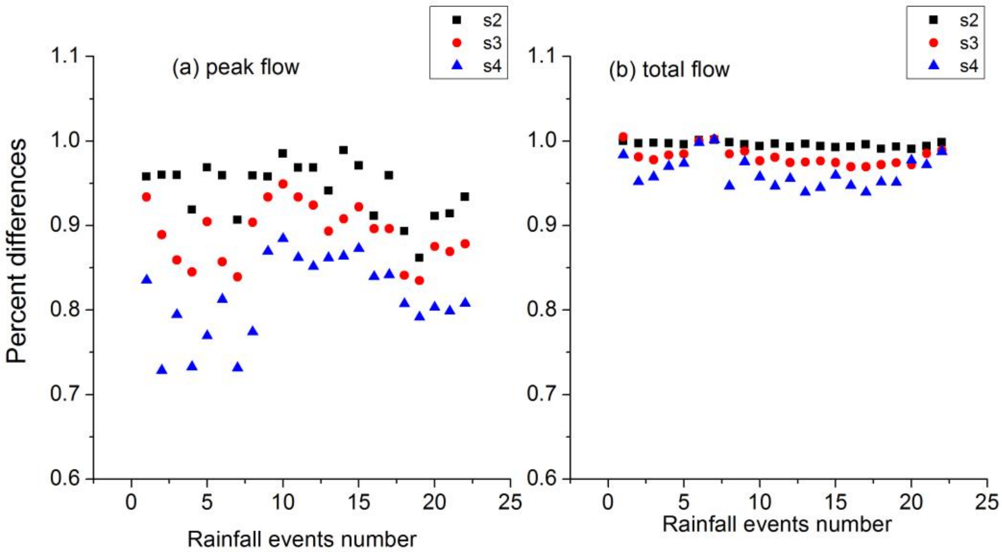

Figure.3 Percent difference in peak flows with respect to S2, S3 and S4 models plotted against those results of S1 model.

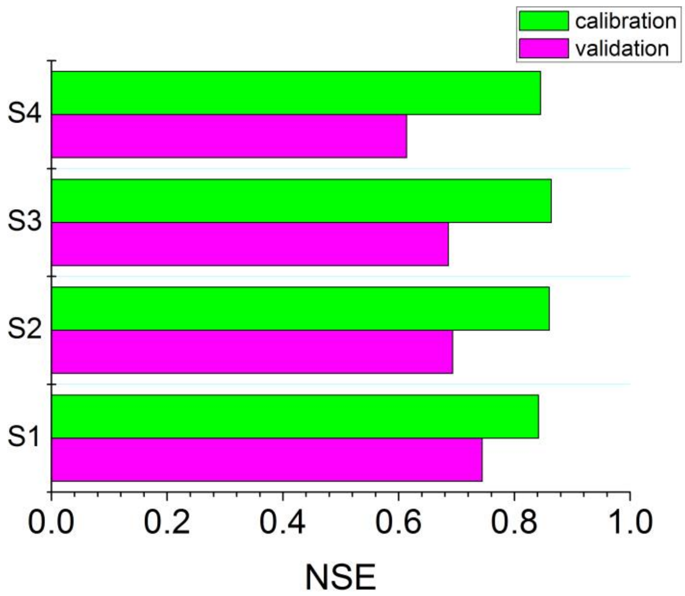

Figure.4 models performances in calibration and validation.

After models calibration, the performance of S2-S4 models in the calibration period are similar to S1 model. The NSE value of all the model exceed 0.84 for calibration sequence. This suggests that calibration processes completely compensate the differences caused by scale effect. However, for the validation period, the performances of models have a declining trend. This indicates that the coarsening of sub-catchment may lead to the loss of certain information and thus hampered the model prediction performances.

3.3 Regionalization performance on a small adjacent area

As stated in section 2.1, the drainage system divides the study area into 2 drainage catchments: a larger one of 41 ha and a smaller one of 5.1 ha. Previously calibration and validation were based on the runoff data observed at outlet of the larger catchment (OT1). For models with different scales, the corresponding optimal parameters values were determined by model calibration. In order to evaluate the universality of those calibrated parameter sets. The calibrated parameters values of the larger catchment models were used in the small catchment models of corresponding spatial resolution.

The results were shown in fig.5. In the aspect of NSE value, the performance of all the scales had a declining compared with catchment alpha. Among them, S1 and S2 model had a relative low declining and S3 model had a larger decrease in NSE performance. This indicated that the best solution found by calibration could be the optimal at entire catchment scale but not at local scale. The reason could be that the equifinality effect was difficult to eliminate and this hampered the small scale performance. Also, there could be errors on model structure and parameterization and global optimal is a result of errors compensating with each other which lead to poorer performance at local scale. The actual reason was probably the combination of above possible explanations.

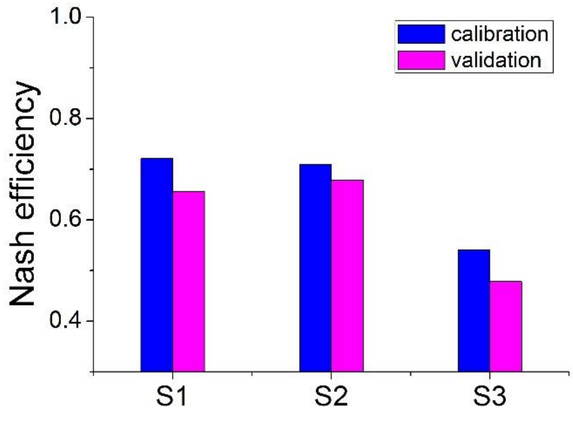

Figure.5 performance of models for regionalization of the OT2outlet during calibration and validation period.

This kind of performance declining at local scale manifest that there were disadvantages of current used single point data calibration method. Thus, the distributed calibration or process based calibration should be advocated in order to improve local scale performance of distributed model. The error identification or reduction of model structure is also important. For example, a model sub-catchment can represent a very small area like single roof top and it can also represent a relative large catchment which main contain hundreds of roof tops and conduits. But we actually expect them to have a same performance pattern. Thus the improvement of model theory is still essential. A detailed distinguish and quantification is beyond the scope of this research but is an interesting topic in future research.

4 CONCLUSIONS

This research attempted to analyze how the model performance and parameter optimization were affected by model grid resolution for a given model structure, SWMM. It had been found that the sensitivities of parameter were basically not affected by spatial resolution. While the output of model was affected by spatial discretization scale. The peak flow decreased with the model upscale process. Those scale effects could be compensated by model calibration and the calibrated models showed satisfied prediction performance. The regionalization of calibrated parameter on a small adjacent catchment had reduced the fidelity of regionalization method. Thus the consideration of scale consistency became more necessary during regionalization.

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