EFFECT OF GEOMORPHOLOGIC RESOLUTION ON HYDROGRAPH AT DIFFERENT SCALES

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The present study investigates effects of grid size of DEMs on hydrograph applying distributed runoff model to five catchments with different scales. This work is carried out in order to give some information to manipulate spatial data and to acquire the reliable result in applications of grid-based model.

The variations of goodness-fit-index and runoff ratio are presented for geomorphologic resolution and catchment scale. It is showed that the fine resolution is appropriate for application to small catchment and the application with different grid sizes mostly meets with satisfactory results.

Key Words : distributed model, scale, DEMs, geomorphology, resolution, hydrograph

1. INTRODUCTION

(1) Distributed model uncertainty

A distributed model is still required as a model describing realistically all hydrological processes in spite of many unsolved problems in real world applications. The distributed approach has the support because of requirement to predict the response of an ungauged watershed or watershed under circumstance change (i.e. altered land use, climate change) in the future (Uhlenbrook *et al.*, 2004). Some studies showed that distributed models being able to delineate spatial heterogeneity have an advantage rather than lumped models for ungauged watersheds (Michaud and Sorooshian, 1994; Refsgaard and Knudsen, 1996).

The simulation of the distributed model includes inevitably some errors connected with model structure, data, calibration and validation. Uncertainty of all models comes from approximate representation of phenomenon in a real world used by theoretical, empirical or conceptual relationships. Many models have been developed to delineate watershed in detail being faithful to an upward approach championed by Freeze and Halen (1996). Unfortunately, more complexity brings more uncertainty. For that reason, some modelers take an interest in a systematic downward approach for the formulation of model with appropriate complexity and uncertainty. Sivapalan (2003) emphasized the requirement of a reconciliation of the model structures and conceptualizations by two 'upward' and 'downward' approaches to develop a model with appropriate complexity at a scale.

Some errors occur while we collect information on watershed characteristic and manipulate the data in order to transform it into input data of the model. Here, we are only concerned with data availability for model application. Normally, the observed or estimated input data is scaled up for computational elements of larger scale than data scale. Because hydrologic response in the elements is treated as homogeneous, data aggregation plays an important role of determination of watershed response. It is important that data is appropriate to the complexity of model structure. Moreover, even when resources are available for collecting suitable data, it is not straightforward to judge whether data will be relevant to modeling the system in detail and in advance (Beck, 1987).

Generally some errors occurred by data and model structure, can be compensated by calibration of model. Runoff data at outlet is used as collective response of a watershed for calibration. By reason of inadequate data and data lack, many distributed models tend to be over-parameterized, with arbitrary and overly complex model structures leading to the problem of equifinality (Beven and Binley, 1992, Beven, 2000). Sometimes calibrated parameter sets cannot be validated owing to the propagation of errors by poor input and output data. Also it may be impossible to certificate variation of water storage in each computational element of a distributed model because of internal information shortage.

(2) Study objectives

For the trustworthy application of a distributed model, simulators need to estimate previously above-mentioned errors. It assists simulators to evaluate the result of simulation and the capability of model. The present study only focused on the error in relation to data at various scale.

Until now, many hydrologists have studied on the effect of Digital Elevation Models (DEMs) because it is based on watershed delineation and stream network. After Vieux and Needham (1993) indicated the importance of the grid cell size, Zhang and Montgomery (1994), Garbrecht and Martz (1995) discussed the geomorphologic resolution. Wang and Yin (1998) presented that the estimation of the mean gradient parameters based on DEMs of 250K (1:250,000) than 24K (1:24000) seemed to improve with increasing terrain complexity. Schoorl *et al.* (2000) quantified the effect of changing the spatial resolution upon modeling the processes of erosion and sedimentation through an experimental multi-scale study of landscape process modeling. Yang *et al.* (2001) indicated that the detailed scaling information had more effect on the hydrological response of higher temporal resolution.

The error in connection with data availability depends on both watershed scale and data resolution. This study investigated the effect of geomorphologic resolution on hydrograph at different scales. This assists some unexperienced users to approach a reliable result through proper data manipulation.

2. METHODOLOGY

An analysis was carried out consisting in a series of experiment with a grid-based runoff model and a lumped model. Each simulation was performed with several grid sizes for five homogeneous catchments.

Table 1 The river width for catchments with different extent.

Extent (km^2)	100	400	900	1600	2500
River Width (m)	50	100	150	200	250

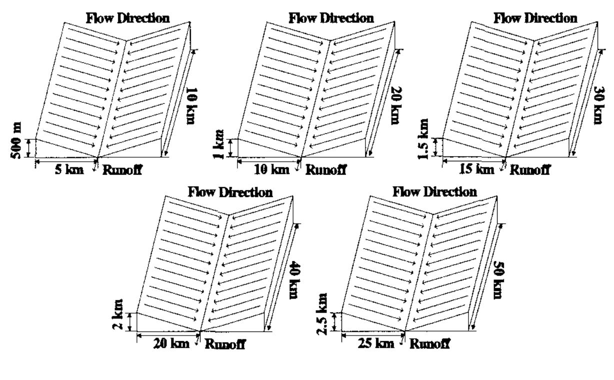


Fig.1 The artificial catchments with area of $100km^2$, $400km^2$, $900km^2$, $1600km^2$, $2500km^2$.

(1) Artificial catchment

Indentifying a hydrologic response of catchment at meso-scale (10^1-10^3 (10^4) km^2) is difficult because of being dominated by both hillslope and channel processes. In this study, catchmentes of meso-scale was constructed artificially with areas of 100 km^2, 400 km^2, 900 km^2, 1600 km^2, 2500 km^2 (Fig. 1) and they were composed of two hillslopes and a channel between hillslopes. The hillslope was composed of several unit-overlands and the slope gradient of the hillslope was equal to a tangent of 0.1. The width of the channel was determined by Eq. (1).

$$B = \alpha A^{0.5} \quad (1)$$

where B is a river width(km), A is an extent of catchment (km^2), α is a coefficient. Here, α was maintained as a value of 1/200. The river widths for different catchments is showed in Table 1.

(2) Geomorphologic resolution

To examine the effect of DEMs resolution on hydrograph, five different resolutions were used for a distributed model and a plane of one grid was considered for a lumped model (Figure 1). For each resolution, all grids have a constant extent and slope. The size of plane for the lumped model is corresponding with the extent of catchment. The computational time of simulation decreases with coarser spatial resolution owing to the decrease of the number of total cells within the catchment.

(3) Data

We were supposed to investigate the effect of

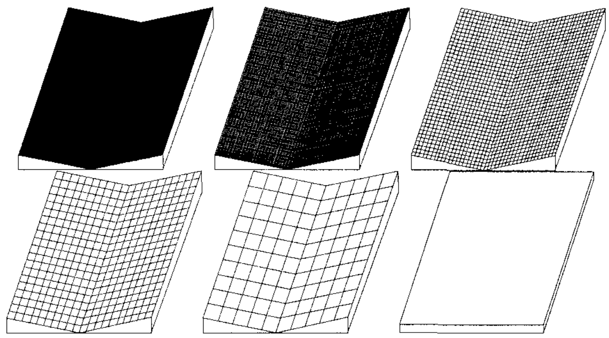


Fig.2 The artificial DEMs at 50×50 m^2, 100×100 m^2, 250×250 m^2, 500×500 m^2 and 1000×1000 m^2 resolution for the distributed model and a plane for the lumped model.

spatial resolution of rainfall in the future. For that reason, an areal rainfall data was considered. Generally, the spatial properties of rainfall can be estimated with areal reduction factor (ARF) for ungaged watershed rainfall or design rainfall. The storm-centered areal reduction factors are defined as the ratio between the maximum areal rainfall within the storm zone for the given area and duration. We employed the ARF for return period of 10-year and duration of 1 hour in the Han-River basin in South Korea by studied Kim *et al.* (2001) and the rainfall intensity from intensity-duration-frequency curve (Yoon, 1997).

The present work is concerned about the effect caused by the only geomorphologic resolution. Therefore we used the average of previously stated rainfall intensity with duration of 1 hour (Table 2). Also, it was assumed that other properties of watershed were homogeneous and that both initial and boundary condition are equal for all applications in order to avoid encountered effects by other factors.

(4) Model description

A simple distributed model was employed to reduce the above-mentioned uncertainty of a model structure. The grid-based model (Fig. 3) brought a good result of simulation in the study of Tsuchida (2002). The catchment is divided into land flow planes and channel segments. In the land, the water is stored in three tanks laid vertically in series. The outputs from top, second, and third tanks express surface, subsurface, and base flows, respectively. The vertical flow from one tank to next tank is computed by a parameter expressed in flow rate.

As surface flow on the overland, water moves with single flowpath. The continuity equation for overland is

$$\frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad (2)$$

Table 2 The average rainfall intensity for catchments with different extent.

Extent (km^2)	100	400	900	1600	2500
Average rainfall Intensity (mm/hr)	61.44	53.99	48.66	44.45	40.94

$$Q = \frac{\sqrt{I}}{n} h^{5/3} \quad (3)$$

where Q is flow discharge, h is the storage of water per unit area, t is time and x is the spatial coordinate. The upstream condition is determined by the flow entering at the upstream end. In Eqs. (2), Q is expressed in Eqs. (3) under Manning's equation, n is Manning's roughness coefficient and I is slope.

The flow in the channel is expressed through the dynamic wave. The continuity equation for channel is

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \quad (4)$$

where q is net lateral inflow per unit length of channel.

The momentum equation for channel is

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial h}{\partial x} - g(S_0 - S_f) = 0 \quad (5)$$

where V is velocity, S_0 is bed slope in relation to gravity force term, S_f is friction slope in relation to friction force term, g is gravity acceleration. The channel sections may be approximated as being rectangular.

The subsurface flow and baseflow are conducted by conceptual model. The water storage of subsurface flow is computed by Eqs. (6) and that of baseflow Eqs. (7).

$$S = K_1 q \quad (6)$$

$$S = K_2 \sqrt{q} \quad (7)$$

where S is stored water depth, q is discharge, K_1 and K_2 are storage constants.

In order to compare with the effect neglecting spatial variability of data, a lumped model was considered. The model maintains the vertical tanks of the distributed model but it regards the catchment as a plane without channels. Therefore the surface flow is computed with only storage constants as the cases of the subsurface flow and the baseflow.

(5) Goodness-of-fit Indexes

To evaluate the performance of each experiment in comparison to the discharge simulated with the grid size of 50m, two goodness-of-fit indexes were considered. The criteria are defined in the equation from (8) to (9).

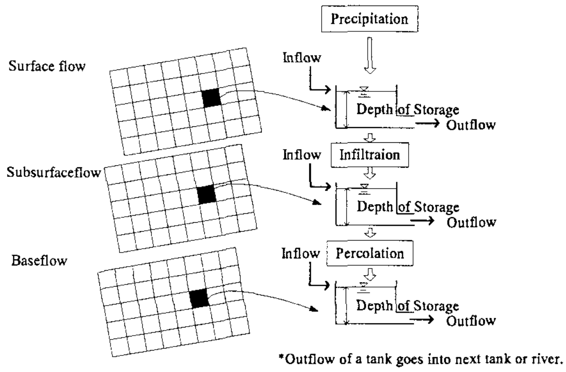


Fig.3 Concept of distributed runoff model

i) EV, relative volume error

$$\mathrm{EV} = \frac{V^o - V^s}{V^o} \tag{8}$$

ii) R^2, model efficiency (Nash and Sutcliffe, 1970)

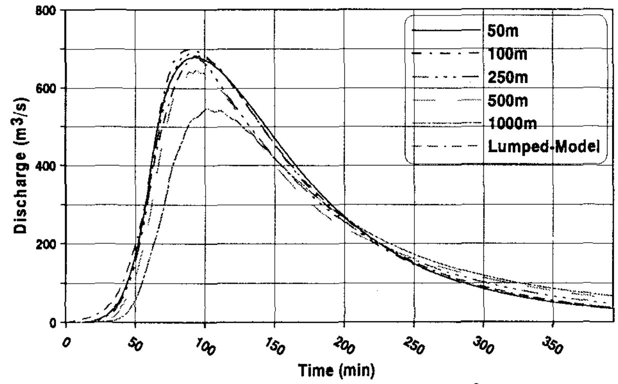
$$R^2 = 1 - \frac{\sum_{i=1}^{n} (Q_i^o - Q_i^s)^2}{\sum_{i=1}^{n} (Q_i^o - \overline{Q})^2} \tag{9}$$

where V^o and V^s are total volumes of simulated hydrographs with reference resolution and other resolution, Q^o and Q^s are discharge simulated with reference resolution and other resolution, n is the number of time steps of the period and $\overline{Q}$ is the mean of the reference discharge.

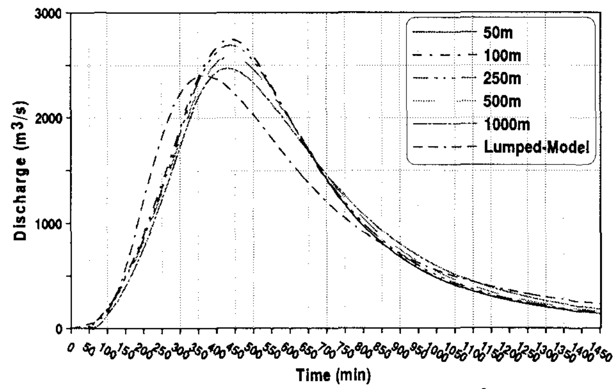
3. RESULTS AND DISCUSSION

Only two sets of hydrographs for cactchment areas of 100 km^2 and 2500 km^2 are shown in Fig. 4 because all hydrographs have similar shapes without regard to catchments. Hydrographs for each resolution of geomorphology are presented in each figure. All hydrographs are displayed from time beginning to rain to time reaching the discharge corresponding with 5% of peakflow of hydrograph for resolution of 50×50 m^2. The hydrographs for catchment with area of 100 km^2 show a little wider range of fluctuation in the peakflow. The time to peakflow lengthens when the area of catchment expends. The reason is that the flow length of overland flow is longer.

Table 3 summarizes the results by both catchment extent and resolution. As the grid size decreases, the peakflow increases with the exception of the grid size of 50 m. In other words, finer resolution generates higher peakflow by the decrease of truncation error. The peakflow of hydrograph for the resolution of 50×50 m^2 is a little lower than that for the resolution of 100×100 m^2. This is because total error increases by the more increase of round error than decrease of truncation error. Overall, the effect of the grid size for peakflow and time to peak is likely to be small and not have any trend.



(a) Catchment with area of 100km^2



(b) Catchment with area of 2500km^2

Fig.4 Hydrographs

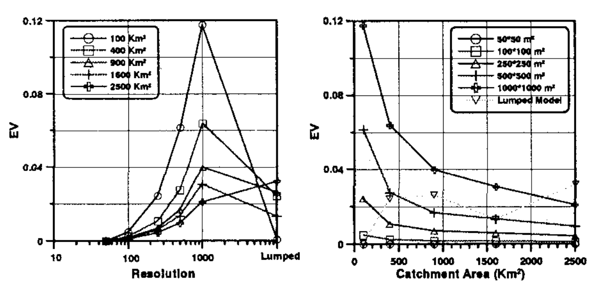
The relationship between the relative volume error (EV) and the geomorphologic resolution is displayed in Fig. 5(a); the relationship between the relative volume error and the catchment extent in Fig. 5(b). EV increases with coarser resolution or smaller area. The model efficiency, R^2 decreases with coarser resolution or smaller scale as shown in Fig. 6. EV and R^2 are sensitive to the resolution of 1000×1000 m^2.

The discharge of lumped model appears to be fitted well to the discharge from the simulation with the resolution of 50×50 m^2 regardless of the extent of catchment. Only, a lagged hydrograph is badly simulated as shown in Fig. 4(b). The time to peak is likely to be faster than those of hydrograph simulated with other resolutions at a larger area. The trends of goodness-fit-indexes differ to those of other resolutions for the distributed model. The lumped model calibrated arbitrarily behaves itself unlike the distributed model.

Table 3 Results of simulation

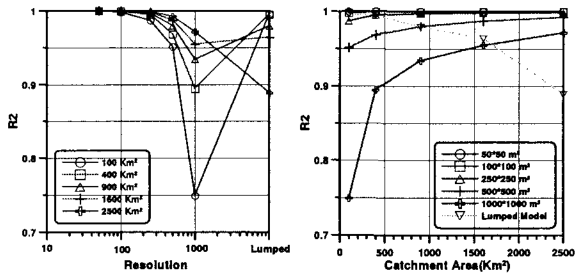
Catchment Extent (km^2)	Resolutaion (m^2)	Runoff (mm)	Model Efficiency (R^2)	Peakflow (m^3/s)	Time to Peakflow (min)
100	50×50	57.94	1.0000	678.08	93.0
	100×100	57.66	0.9979	698.05	89.5
	250×250	56.53	0.9870	687.25	88.5
	500×500	54.37	0.9513	645.03	94.0
	1000×1000	51.13	0.7493	545.87	101.5
	Lumped	57.90	0.9956	681.51	96.0
400	50×50	50.18	1.0000	1372.08	169.5
	100×100	50.05	0.9991	1389.19	166.0
	250×250	49.64	0.9946	1320.11	164.5
	500×500	48.80	0.9683	1265.3	161.0
	1000×1000	46.97	0.8945	1181.12	174.5
	Lumped	48.96	0.9947	1367.37	164.0
900	50×50	44.36	1.0000	1944.62	258.5
	100×100	44.28	0.9995	1955.49	254.0
	250×250	44.05	0.9970	1886.32	253.0
	500×500	43.61	0.9798	1771.44	247.0
	1000×1000	42.60	0.9340	1703.76	249.5
	Lumped	43.20	0.9793	1838.85	235.0
1600	50×50	39.35	1.0000	2398.24	351.5
	100×100	39.29	0.9997	2402.76	346.5
	250×250	39.12	0.9980	2339.42	345.0
	500×500	38.82	0.9871	2219.2	345.0
	1000×1000	38.15	0.9548	2127.94	340.5
	Lumped	38.83	0.9639	2150.55	320.0
2500	50×50	35.51	1.0000	2747.86	444.0
	100×100	35.47	0.9998	2748.64	439.5
	250×250	35.36	0.9987	2691.63	437.5
	500×500	35.17	0.9923	2583.05	439.0
	1000×1000	34.77	0.9714	2469.97	431.5
	Lumped	34.38	0.8889	2401.61	367.0

Contour maps of above-mentioned errors are drawn in Fig. 7 and 8 in order to understand more easily how the two errors are changing in resolution



(a) For resolution (b) For catchment

Fig.5 Relative volume error (EV)



(a) For resolution (b) For catchment

Fig.6 Model efficiency (R^2)

catchment area with the exception of the lumped model showing different trend. Reliability of a model is gained when relative volume error is low and model efficiency is high. From contour maps, we can grasp that the reliability increases with finer grid size or at larger catchment. We should consider the different distortion if we run same errors because the gradient of line corresponding to certain error is not a constant. For instance, a double resolution requests 5 times area for the relative volume error of 0.01 while less than double resolution requests 5 times area for the error of 0.002. The gradient of relative volume error changes with wider range than it of model efficiency.

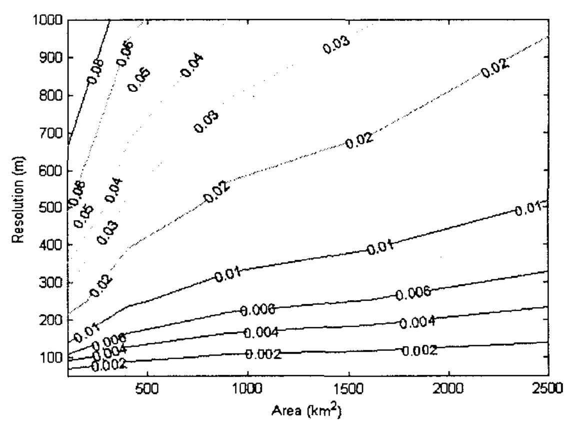


Fig.7 Relative volume error (EV)

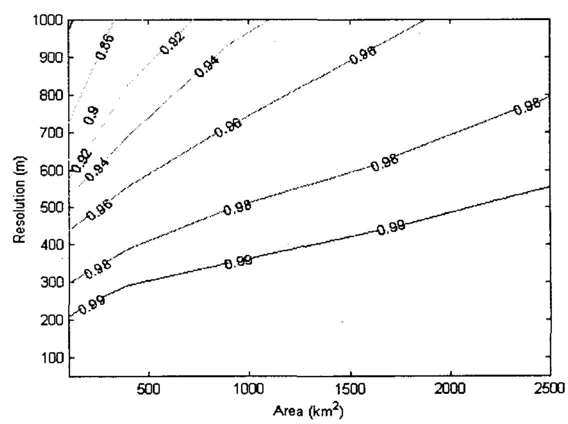


Fig.8 Model efficiency (R^2)

4. SUMMARY AND CONCLUSIONS

The uncertainty of the distributed hydrologic model is topical in hydrologic field. The problem is not simple because it is related to all procedure of application of model as model structure, data, calibration and validation. Generally, the resolution of DEMs has mostly been studied in the issue of spatial resolution of the distributed model. We are interested in the effect of the aggregation of the spatial data at various scale with the grid-based model. As the first step, the effect of the geomorphologic resolution on hydrograph was investigated keeping another data homogeneous. The distributed model with other grid size and the lumped model were applied to the five artificial catchments at different scales.

The results show that the hydrographs have similar shape, the difference between peakflows is small and the times to peakflows are almost same in all cases. The values for relative volume error are placed below 0.12. The model efficiencies have mostly the high values over 0.9. The contour maps show graphically that grid size is appropriate for reliable simulation of the distributed model at any scale. In this study, the figures show that simulation of smaller catchment requires finer data resolution as expected in order to reduce both errors.

In generally, the lumped model gives satisfactory results in spite of limitation in the simulation for lagged hydrograph in large area. The lumped model might be available for small and homogeneous area. The lumped model should carefully be used because the calibration of lumped model can bring different results according to both experience and judgment of hydrologist. This tells that the lumped model may not guarantee high model efficiency for all applications.

It is no wonder that spatial data have different degree of heterogeneity. The grid-based model solving FDE (Finite Difference Equation) is affected by the magnitude and spatial variation of data. The effect of geomorphologic data investigated in this study will be compared with the effect of another spatial data. It will be considered in the future. In the application of a grid-based model, error contour map for spatial distribution of data is able to give some information for manipulation of spatial data and evaluation of model capability.

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