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Disaggregation of upslope catchment area and steepest slope for transferring geomorphometric information across scales

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Abstract Higher resolution upslope catchment area values at finer grid sizes are lost, and slopes are underestimated, when DEMs with a coarse grid resolution are used. Thus dominating geomorphological parameters are directly influenced by the scale of DEM resolution. To overcome this problem, downscaling methods have been derived for both upslope catchment area and slope by introducing the concepts of number of sub-grids, influence factor and fractal method for scaled steepest slope. An application of the disaggregation method has been shown in the Kamishiiba catchment (210 km^2) in Japan, with the successful derivation of the target fine resolutions for upslope catchment area and slope information from 1000 m DEM resolution.

Key words downscale; upslope catchment area, steepest slope, ungauged basin

INTRODUCTION

One of the major challenges in hydrological geomorphology is the understanding of scale dependencies of forms and processes so that such an understanding would allow observations made at convenient scales to be extrapolated to other less well observed scales. This implies that the need for continued and sustained research on scale issues is therefore self-evident (Tachikawa, 2004).

Blöschl & Sivapalan (1995) refer to scaling as the transfer of information between different spatial (or temporal) lengths. The "transfer of information" may consist in mathematical relationships, statistical relationships, or observations describing physical phenomena. The problem of transferring information gained at one scale for making predictions at a different hydrological scale is a scaling problem (Beven, 1995). Lack of methods for the translation of the scale dependence relations into effective hydrological models poses a serious problem for the ungauged basins of developing countries, where either only coarse resolution DEM data is available or where the information gained at one scale is to be utilized in making predictions at other (usually lower) scales.

To address the scale problems in hydrology, several studies have done research on self-similarity in river basin channel-network geomorphology and topology (Gupta & Waymire, 1989; Rodriguez-Iturbe & Rinaldo, 1997). Dietrich & Montgomery (1998) argue that until the grid scale of the information drops well below the scale of influence of a particular process, we shall be wrestling with the compromise between using physical laws and analysing large landscapes.

Topography-driven hydrological models (e.g. Beven & Kirkby, 1979; O'Loughlin, 1986; Woods *et al.*, 1997) represent an attempt to combine the computational and parametric efficiency of a distribution function approach with the link to a physical theory. In such models, the dominating geomorphometric parameters that account for the hydrological similarity condition is also strongly influenced by the resolution of DEM used. This results in parameter inconsistency and predictive uncertainty across scales.

In this research, DEM resolution effect on the dominating geomorphological features is analysed and disaggregation/downscaling methods for upslope catchment area and steepest slope are developed to obtain the finer resolution geomorphological information from topographic observations made at convenient scales. The downscaling methods proposed by this research can be utilized in a transferable hydrological model development for macroscale/mesoscale ungauged basins to overcome the limitations of the aggregation approach that assumes a hydrological model applicable at small scales can be applied at large scales using the same effective parameter values.

DEM RESOLUTION EFFECT ON GEOMORPHOMETRIC INFORMATION AND ITS SOLUTION

Upslope catchment area

In hydrological geomorphology, upslope catchment area is a key variable because of its intrinsic capability to describe the nested aggregation structure embedded in the fluvial landforms and its important physical implications (Leopold & Maddock, 1953). In a DEM-based distributed hydrological model, upslope catchment area at a point in a catchment is the number of pixels draining through that point (Rodriguez-Iturbe & Rinaldo, 1997). Figure 1 shows the frequency distribution of the upslope catchment area at four different DEM resolutions in the Kamishiiba catchment (210 km^2) in Japan, without taking into account the scale effect.

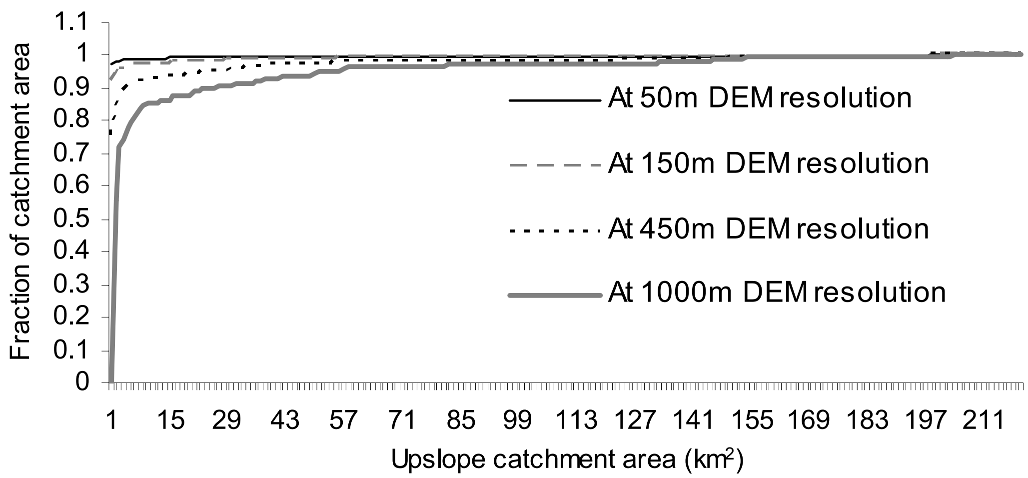

Fig. 1 Comparison of distribution functions of upslope catchment area obtained from different DEM resolutions in the Kamishiiba catchment (210 km^2).

A distinct decrease in the finer values of upslope catchment area is seen as the fraction of catchment area in Fig. 1 as the resolution of DEM becomes coarser. In Fig. 1, the smaller upslope catchment area less than 1 km^2 that appears over 97% in 50 m DEM resolution is completely lost when 1000 m DEM resolution is used. Figure 2 further clarifies this. In Fig. 2 (a), it is seen that at 50 m DEM resolution, most of the parts of the catchment (97% defined by Fig. 1) are covered by the upslope catchment area of less than 1 km^2. Figure 2(b) shows that at 1000 m DEM resolution there is no grid having upslope catchment area less than 1 km^2.

Finer areas smaller than the grid resolution of DEM used are lost as the larger sampling dimensions of the grids act as a filter. When a finer resolution DEM is used, the smaller upslope catchment area, that is the area of finer grid resolution, is achieved. From this point of view, the number of sub grids N_s (see Fig. 3) is introduced to derive scaled upslope catchment area as:

$$C_{i,scaled} = \left(\frac{C_i}{N_s I_f} \right) \tag{1}$$

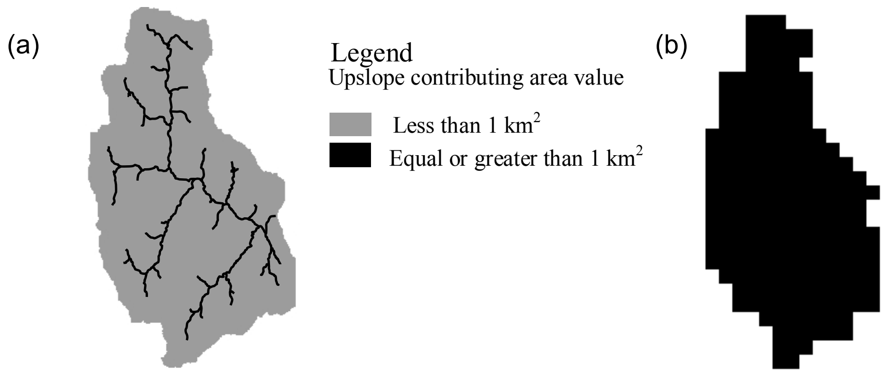

Fig. 2 Comparison of upslope catchment area less than 1 km^2 from: (a) 50 m DEM resolution and (b) 1000 m DEM resolution in the Kamishiiba catchment (210 km^2).

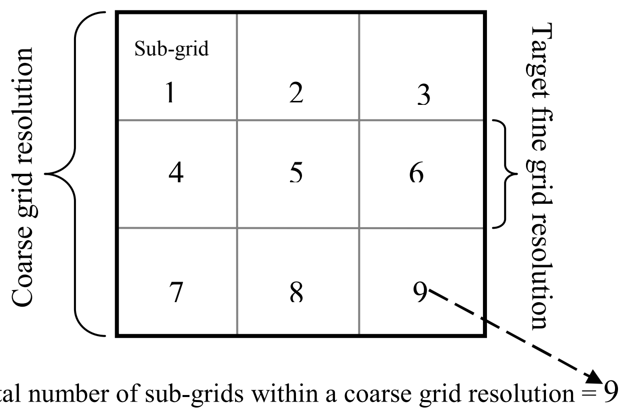

Fig. 3 Concept of N_s as number of sub grids within a coarse grid resolution.

where the suffix i is a location in a catchment; C_i is the upslope catchment area obtained from a coarse resolution DEM; $C_{i,scaled}$ is the scaled upslope catchment area at a point i and I_f is introduced as influence factor.

Figure 1 shows that as the upslope catchment area becomes bigger, the distributions of the upslope catchment area values given by coarse and fine resolution DEMs become closer. Thus the influence of N_s on C_i must gradually decrease in equation (1) as C_i becomes larger. For this reason, in equation (1) the influence factor I_f is introduced. From the discussion of influence of N_s on C_i, the following three points are proposed:

(a) At the catchment divide portion where the upslope catchment area in a coarse resolution DEM is a single coarse resolution grid area, the value of influence factor I_f in equation (1) is equal to 1 showing that N_s has complete influence on C_i.
(b) Considering the upslope catchment area given by coarse resolution DEM and target fine resolution DEM are equal at the outlet of the catchment, the value of influence factor I_f in Equation (1) is equal to $\frac{1}{N_s}$ showing that N_s has no influence on C_i.
(c) Exponential decay of influence factor is taken from the value 1 defined in (a) to $\frac{1}{N_s}$ defined in (b) as the upslope catchment area gets bigger. Thus, I_f is defined as:

$$I_f = e^{\left\{\frac{(1-N_i)H}{N_o}\right\}} \tag{2}$$

where, N_i is the number of the coarse resolution grids contained in the upslope contributing area at a location i in the catchment; and N_o is the number of the coarse resolution grids contained in the upslope catchment area at the outlet of the catchment. H in equation (2) is introduced as harmony factor. Considering the influence of N_s on C_i in Equation (1) is almost negligible at the outlet of the catchment, where $N_i = N_o$ and $I_f = \frac{1}{N_s}$, the value of H can be as:

$$N_s e^{-H} = 1 \tag{3}$$

Equations (1) and (2) give a downscaling method for the upslope catchment area as:

$$C_{i,\,scaled} = \left(\frac{C_i}{N_s e^{\left\{\frac{(1-N_i)H}{N_o}\right\}}} \right) \tag{4}$$

Steepest slope

In hydrological and soil-erosion process models, the most important parameters related to DEMs are slope and aspect. Figure 4 shows the frequency distribution of the steepest slope at four different DEM resolutions in the Kamishiiba catchment (210 km^2) without taking into account the scale effect. Figure 4 shows that slopes are underestimated as coarser resolution DEMs are used.

Following the fractal theory in topography and slope (Klinkenberg & Goodchild, 1992; Zhang *et al.*, 1999) the downscaling method for the steepest slope of the target resolution DEM is developed as:

$$\theta_{scaled} = \alpha_{steepest} d_{scaled}^{(1-D)} \tag{5}$$

where θ_{scaled} is the downscaled steepest slope distance; d_{scaled} is the steepest slope distance of the target resolution DEM; D is the fractal dimension; $\alpha_{steepest}$ is a coefficient. The distance variation of d_{scaled} is made as per the direction of the steepest slope in the coarse resolution DEM. Hence as an example in Fig. 5(b), the d_{scaled} is taken as $\sqrt{\Delta x^2 + \Delta y^2}$ which is in the same direction to that of the coarse resolution DEM steepest slope distance $\sqrt{dx^2 + dy^2}$ in Fig. 5(a).

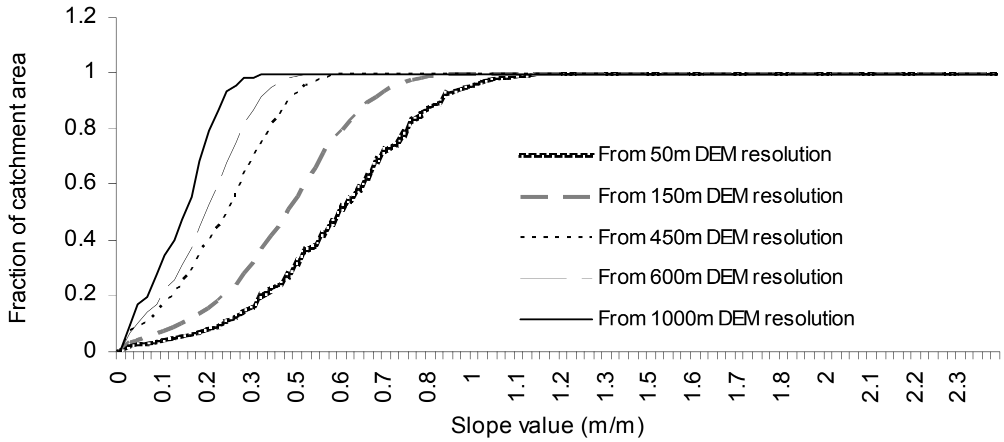

Fig. 4 Comparison of steepest slope distribution function obtained from different DEM resolutions in the Kamishiiba catchment (210 km^2).

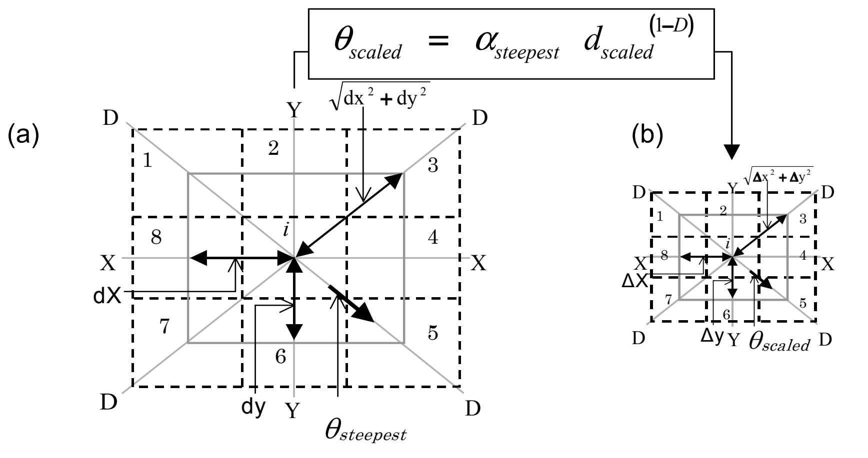

Fig. 5 Method to downscale steepest slope at a location *i* of the 3 × 3 moving window pixels: (a) steepest slope structure of the available coarse resolution DEM having grid size of dx and dy in X-axis and Y-axis, respectively; (b) scaled steepest slope structure of the target resolution DEM having grid size of Δx and Δy in X-axis and Y-axis respectively.

In equation (5), the fractal dimension D is related to standard deviation of elevation σ (Zhang *et al.*, 1999) in 3 × 3 moving window pixels defined in equation (6) as:

$$D = 1.13589 + 0.08452 \ln \sigma \tag{6}$$

A method of deriving the coefficient $\alpha_{steepest}$ is proposed in this research in which $\alpha_{steepest}$ values are derived directly from the steepest slope of the available coarse resolution DEM. In Fig. 5(a), where the steepest slope is shown in diagonal direction, $\alpha_{steepest}$ at that location i is given by equation (7) as:

$$\alpha_{steepest} = \frac{\theta_{steepest}}{\left(\sqrt{\mathrm{dx}^2 + \mathrm{dy}^2}\right)^{(1-D)}} \tag{7}$$

where $\theta_{steepest}$ is the steepest slope using the coarse resolution DEM. More details of the derivation of equation (5) is given in Pradhan *et al.* (2004).

RESULTS AND DISCUSSION

Downscaling of upslope catchment area

The method to downscale the upslope catchment area is applied to the Kamishiiba catchment (210 km^2) in Japan. In contrast to Fig.1, Fig. 6 (a), (b), (c) and (d) show that

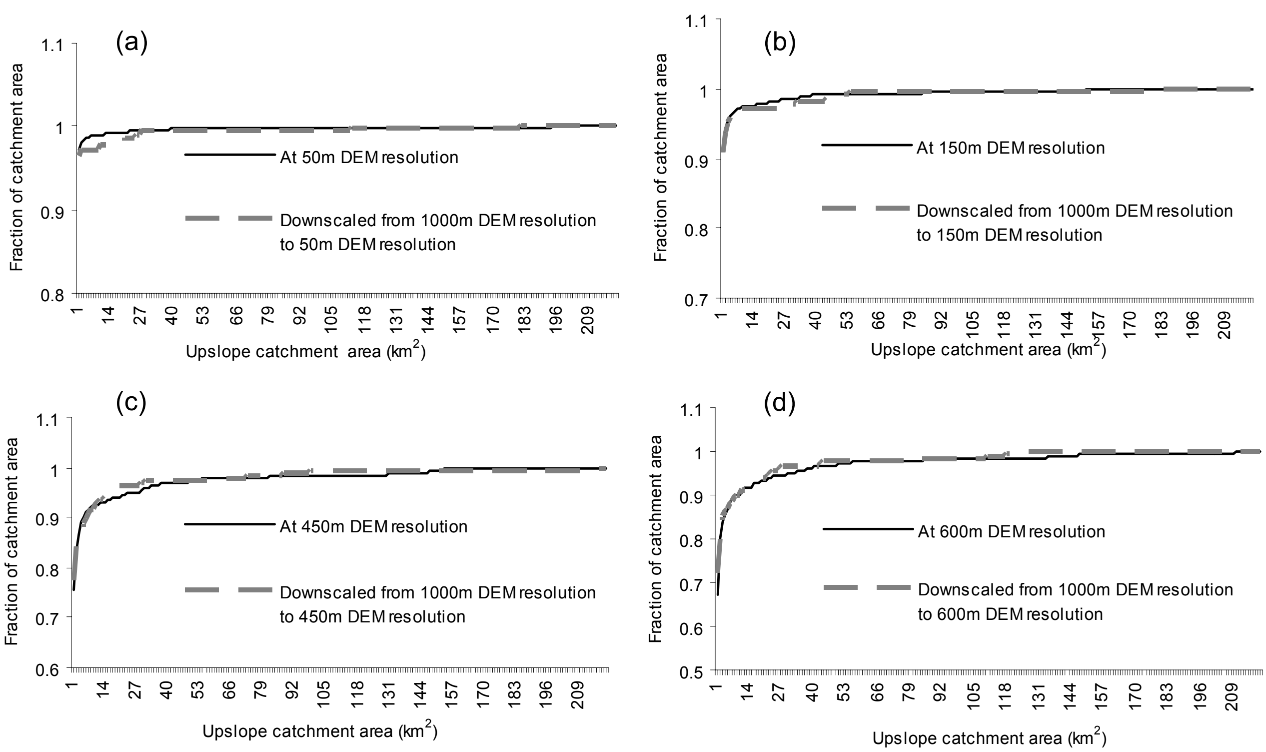

Fig. 6 Comparison of distribution function of upslope catchment area from 1000 m grid resolution DEM to finer grid resolution DEM and the distribution function of the upslope catchment area at the fine scale in the Kamishiiba catchment (210 km^2). (a), (b), (c) and (d) are the comparisons for 50m, 150m, 450m and 600 m grid resolution, respectively.

the frequency distribution of upslope catchment area from the 50 m DEM resolution, 150 m DEM resolution, 450 m DEM resolution and 600 m DEM resolution, have matched with the downscaled upslope catchment area frequency distribution from 1000 m DEM resolution to the respective target fine DEM resolutions by using equation (4). This shows that the proposed method to downscale the upslope catchment area given by equation (4) can be successfully used to obtain the higher resolution of upslope catchment area at finer grid sizes by using only a coarse DEM resolution.

Downscaling of steepest slope

Figure 7 shows the comparison of the scaled slope distribution function from 1000 m DEM resolution to target fine resolution DEMs by using equation (5) and the distribution function of the slope at that fine scale DEMs, respectively, in the Kamishiiba catchment. Figure 7(a), (b) and (c) show a close fit of the frequency distribution of the scaled slope from 1000 m grid resolution DEM to 600 m, 450 m, 150 m grid resolution DEMs, while Fig. 7(d) shows that equation (5) overestimated the slope when downscaling from 1000 m to 50 m DEM resolution. In equation (5) slope is a function of the measurement scale on the assumption that topography is unifractal in a specified range of measurement scale. This concept of unifractal can break at very fine scales (Klinkenberg & Goodchild, 1992). The break in the unifractal at fine scales and its solution method is a further research work.

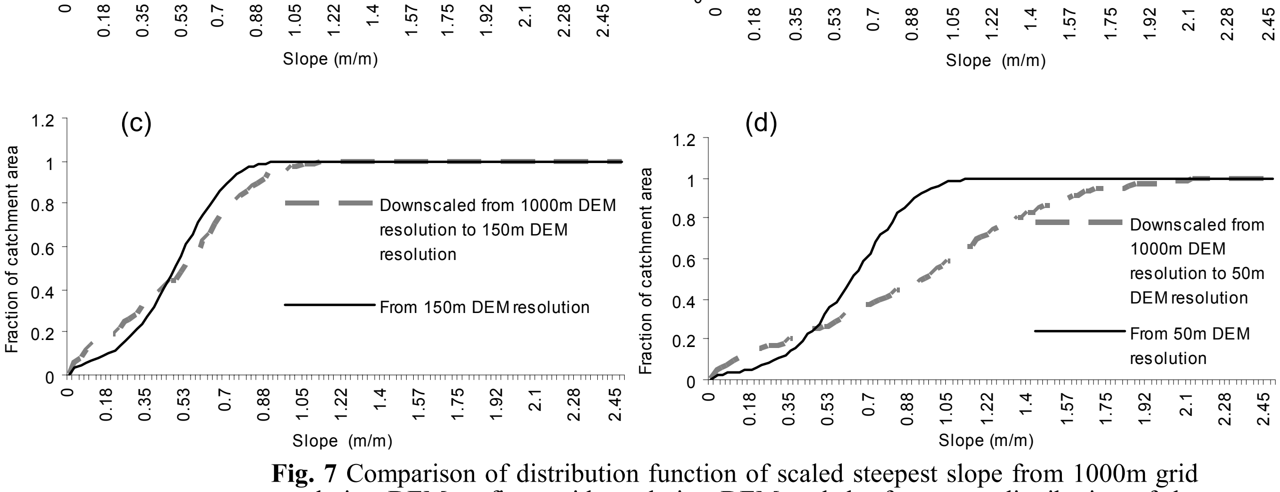

Fig. 7 Comparison of distribution function of scaled steepest slope from 1000m grid resolution DEM to finer grid resolution DEM and the frequency distribution of the steepest slope at the fine scale in the Kamishiiba catchment (210 km^2). (a), (b), (c) and (d) are the comparisons for 600m, 450m, 150m and 50m grid resolution, respectively.

CONCLUSION

In this research, methods to downscale the upslope catchment area and steepest slope are developed to solve the effect of DEM resolution on the upslope catchment area and slope. The downscaling method has been successfully applied at the Kamishiiba catchment (210 km^2) in Japan to obtain the higher resolution geomorphometric information. The downscaling methods can be utilized in topography driven models to match the scale of model application and the scale of the parameter identification for reducing parameter inconsistency and predictive uncertainty in a macroscale/meso-scale ungauged basin (Pradhan *et al.*, 2006). It is hoped that the findings of this research seeks its applicability as a tool to a wide range of boundary as per the scale problems in hydrological geomorphology and solution approach is concerned.

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