THE DEFINITIONS OF STREAM HEADS ON DEMS AND THEIR EFFECTS ON STREAM NUMBERS AND LENGTH

Daichi NAKAYAMA

Abstract Three topographical parameters, drainage area, exterior links and valley depth, are calculated as the criteria to define stream heads on digital elevation models in this study. Their variations effect on Horton-Strahler ordered stream numbers and length. Three topographical parameters are classified into two types. "Successive" and "non-successive" parameter is determined by whether it increases successively from upstream or not. The differences between two parameters cause whether stream numbers decrements and length increments associated with threshold increments have fluctuations or not. Moreover, order transition styles of successive parameters are single-directional, such as lower order to higher order stream, and those of non-successive parameters are bi-directional. This indicates that Horton-Strahler ordered streams are largely influenced by the threshold parameters.

Key words: DEMs, stream head definition, drainage area, exterior links, valley depth

1. Introduction

Topographical properties of drainage basins are extracted from stream networks. These properties determine characteristics of hydraulic phenomena. For example, a planimetric shape of stream network is capable of being one of limit factors to predict runoff time. The automatic extraction of drainage networks on digital elevation models (DEMs) allows us to measure various topographical properties of drainage basins, to analyze topology of stream networks and to predict runoff by distributed runoff models. The first step of this procedure is the definition of stream heads.

Several definitions of stream heads on topographical maps have been used in previous studies. For example, the points of bends in contour lines (Takayama 1972), the points where a valley width is larger than a valley length (Sakaguchi 1965) and the end points of "blue lines" drawn on maps (Horton 1945; Jarvis 1976) have been adopted as stream heads traditionally. However, these are manual methods, and have several problems, such as differences of skill and experience among operators that cause low qualities and subjective results about extracted stream networks. Furthermore, it needs much labor.

On the other hand, the extracting stream networks from digital elevation models

(DEMs) with computers can avoid these problems (Marks *et al.* 1984; O'Callaghan and Mark 1984). DEMs and computers provide automatic extraction of stream networks which have less subjective results than that from above-mentioned manual method. The most advantageous feature of computer-aided extraction of stream networks is that we can define parameters such as drainage area for all grid points. Nevertheless, there arise two different problems on DEMs and computer method. First, the automatically extracted stream channels do not coincide with actual ones on low relief and flat plains, such as basin floors and alluvial fans. This problem is originated from quantization of height and grid space of DEMs. Second, the three streams can confluent simultaneously with a referenced grid point when applying the 4-direction chain code. This largely influences Horton's bifurcation ratios and length ratios. To avoid the first problem, vectorized channel location data may be useful. If the target basins are located in high relief mountains, the automatically extracted stream networks will coincide precisely. Because the valley bottom flat will be narrow compared to the grid space of DEMs. For the second problem, we need to eliminate the flow lines that do not represent streams on the actual land surface. To do so, stream heads must be set on the grid points where a given threshold, such as drainage areas or external links, is satisfied.

At first, we have to check the way of definition of the stream on DEMs, then evaluate its effects to subjective parameters such as Hortonian parameters and other topographical measures of drainage basins. Helmlinger *et al.* (1993) and Snell and Sivapalan (1994) adopted a drainage area and a magnitude of exterior links as threshold definitions, respectively. However, their ways are not simulative to manual methods. The purposes of this study are (1) to define a new threshold criterion of DEM-based stream networks which simulates completely a manual method, (2) to check its effects on stream numbers and length by using the threshold defined here, and (3) to evaluate this method by comparing our results to those in previous studies.

2. The Establishments of Stream Networks and the Criteria Calculations

Northeast of the Southern Alps region, Central Japan, is selected as the study area. Digital Map 50m grid (Elevation) —approximately 50m grid-interval resolution— provided by Geographical Survey Institute Japan are used as the basic dataset.

The complete drainage direction matrices (DDMs) without loops, crossovers, stream interruptions, and branchings are created by the use of a "flood-flow" algorithm (*e.g.*, Nogami 1991 1995). DDMs are two dimensional data arrays that indicate the flow directions of all grid points. This algorithm fixes drainage directions of all grid points by the steepest descent between a given point and eight neighbors. Therefore, this algorithm is useful for high-relief mountainous region like this study but not suitable for completely flat places. Each grid point in DDMs has a drainage area, which equals to the number of upper grid points multiplied by unit area. Calculated values of drainage areas are located at the grid point of basin outlet (Nogami 1991). Then, all grid points that flow down to an outlet are located in the same drainage basin. The threshold of basin area is not a specific value but has in fact a range. If the specific value is regarded as the threshold, the drainage area along the flow lines exceeds the threshold after confluence. So the threshold must be regarded as a range, and the threshold of basin outlets must be equal to the largest drainage area within the threshold range. This threshold must be limited to the equal integer values of the logarithm of the drainage area. Then, the base of logarithm must be 2 for taking the confluence of streams into consideration (Yoshiyama 1994).

Two drainage basins shown in Fig. 1 with approximately 10-20km² area (between 4, 096 and 8,192 grid points) are extracted as sample sites from the DDMs. The reasons why larger drainage basins are not selected are explained as follows: (1) the definition of stream heads is the main point to be discussed in this study, and treatment of the higher order streams is currently out of purpose; (2) as explained above, if the objective drainage basins include flat places, the extracted drainage networks have disagreements with actual stream networks.

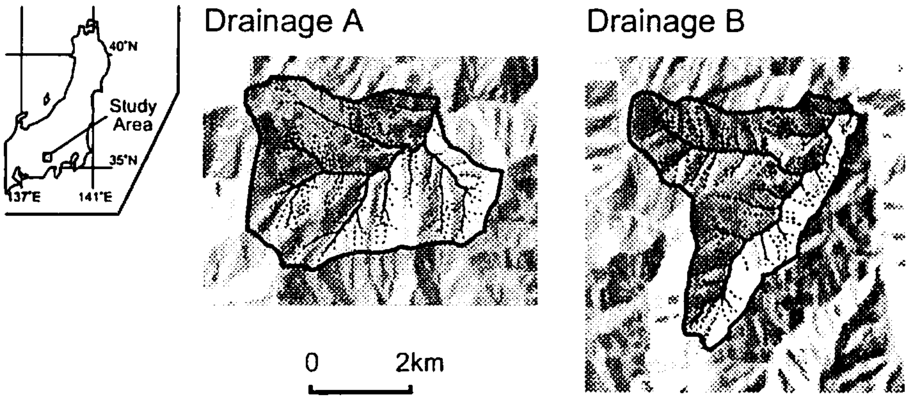

Fig. 1 Shaded-relief and stream lines of study drainage basins
Study basins are located in Southern Alps region of Central Japan. Both basins have approximately 10 to 20 km² areas (between 2,048 to 4,096 grid points). Shaded-relief maps are obtained from Digital Map 50m grid (Elevation) provided by Geographical Survey Institute Japan. Stream lines are extracted by a manual method from 1:50,000 topographical maps. Stream heads are defined to the bending points of contour lines. Black lines are basin perimeters. Dashed lines are first order streams, thin lines are second order steams, and thick lines are third or higher order streams.

The width function has important information to analyze the characteristics of the drainage network (*e.g.*, Jarvis 1972; Rigon *et al.* 1993; Kirkby 1993). This function shows the frequency distribution. The distance from basin outlet is taken as x-axis and the frequency of distances is taken as y-axis. Idealistically, a width function of a narrow-shape drainage basin is flatter than that of a round-shape basin. Figure 2 shows the width functions of both drainage basins. The increase of the width functions in drainage A is rather rapid than that of drainage B. This indicates that numbers of short and middle

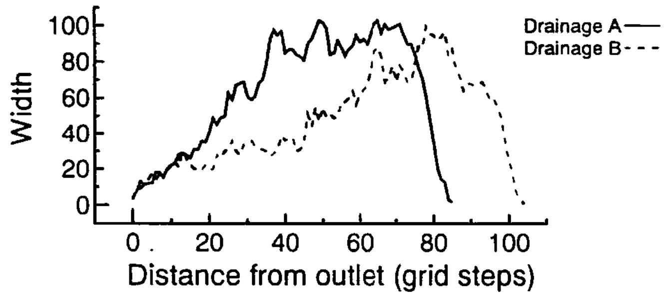

Fig. 2 Comparison of width functions between drainage A and drainage B
Black line is a width function of drainage A, and dashed line is a one of drainage B.

distance points from the outlet of drainage A are larger than those of drainage B. Furthermore, drainage A is round, but drainage B is relatively narrow. The peak of drainage B is located on the right of that of drainage A. This indicates that the upstream width of drainage B is wider than that of drainage A. This is caused by the combination of two narrow basins of drainage B that share one outlet.

In this article, streams are flown out from the points where a given threshold is satisfied. Thresholds based on three kinds of criteria models, drainage area (D_A), exterior links (E_L), and valley depth (V_D) are tested (Fig. 3). Nogami (1995) defined "local" topographical parameters as estimated by using solely the values of a given point and neighbors. Thus, all criteria models, D_A, E_L and V_D, are "local" and "point" parameters. D_A indicates the number of upper points of each grid point (Fig. 3-A), as shown above. E_L shows the number of exterior links of each grid point (Fig. 3-B). These two criteria are successively increase from upstream. V_D is defined here as follows (Fig. 3-C): $h(x, y)$ is an altitude of the given point, and $h(x_0, y_0)$ is an altitude of the flow down point from $h(x, y)$. H_0 is half of the relative height between $h(x, y)$ and $h(x_0, y_0)$. $H(x_1, y_1)$ and $h(x_2, y_2)$ are the altitude of right and left side of flow direction, respectively. The relative height between $h(x, y)$ and $h(x_1, y_1)$ is defined as H_1, and between $h(x, y)$ and $h(x_2, y_2)$ as H_2. Those relative heights, H_0, H_1 and H_2 are calculated correctly whether the flow direction is cardinal with grid side or diagonal (Fig. 3-C1 and C2). The average of (H_0-H_1) and (H_0-H_2) is defined as valley depth. Figure 4 shows V_D distributions of two drainage basins, and indicates that an increase of V_D is not successive from upstream. This criterion indicates that large values correspond to higher order streams in Fig. 1. On the contrary, small values on the mountainside indicate linear slopes. After all, this criterion is equivalent to the bending angle of contour lines. Therefore, the drainage networks by use of V_D correspond to a simulation of a manual method that sets the bending points of contour lines on the topographical maps to stream heads.

A set of drainage networks derived from D_A is called Type A, E_L is the Type B, and V_D is Type V. For D_A and E_L, $\mathrm{int}(\log_2 D_A)$ and $\mathrm{int}(\log_2 E_L)$ are adopted as the thresholds. For V_D, the observed value is taken as the threshold. Thresholds take a range from 1 to 15 in the case of Type A and Type E, from 0 to 30 in the case of Type V. The points that

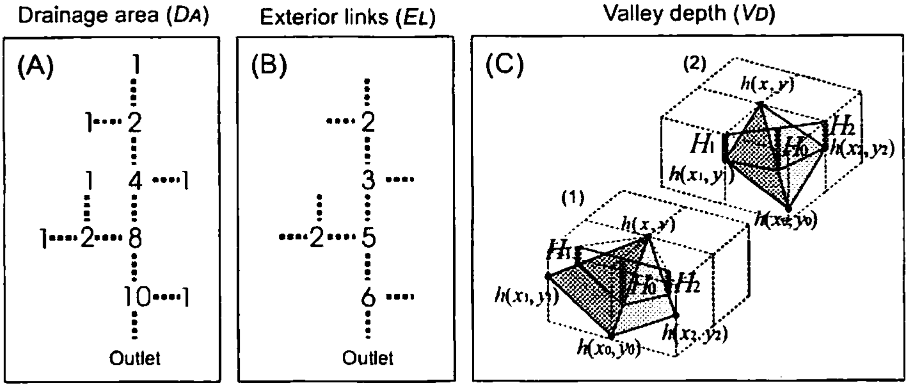

Fig. 3 Definitions of three criteria models
(A) is drainage area (D_A), (B) is exterior links (E_L) and (C) is valley depth (V_D). The numbers of drainage area and exterior links indicate numbers of upper points and those of exterior links, respectively. Both criteria increase successively from upstream to downstream. Dashed lines of (C) indicate ideal grid sides of DEMs. $H(x_1, y_1)$ are altitude of given points. Gray triangles indicate pseudo-landsurfaces that are obtained from DEMs. V_D is calculated correctly whether the flow direction is cardinal (1) with grid side or diagonal (2).

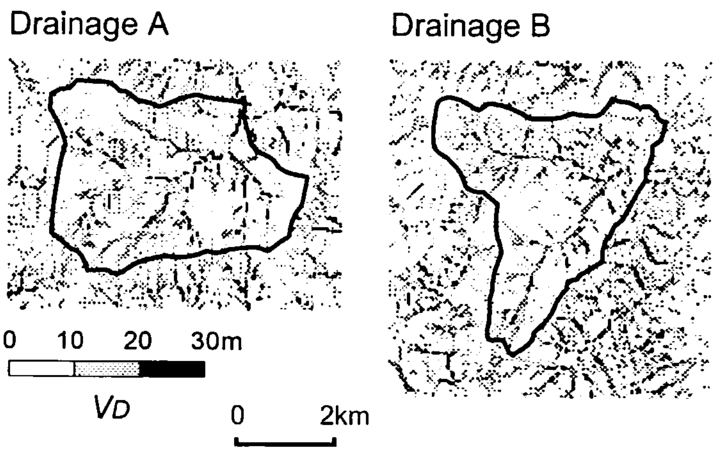

Fig. 4 Spatial distributions of valley depth (V_D)
Black lines are basin perimeters. Values of V_D are divided into three classes (0 to 10, 10 to 20 and 20 to 30) in this figure. V_D is equivalent to the bending angle of contour lines on topographical maps. V_D does not increase successively from upstream to downstream.

fulfill a given threshold are set to the stream heads. If the multiple stream heads are set on the same flow line, the upper is regarded as a stream head. All types of stream networks are ordered by Horton-Strahler ordering system. In the case of DEMs and computer method, three or more streams can be confluent simultaneously. Therefore, the Horton-Strahler ordering system is modified to suit in this case (Yoshiyama 1989; Nogami 1995). Then, steam numbers and average length of streams of all types are calculated.

The scatter diagrams among three criteria are shown in Fig. 5. There exists an obvious correlation between D_A and E_L. However, the correlation between small D_A and small E_L has a large variance. It means that Type A and Type E form almost the same pattern in the case of the large thresholds. On the other hand, in the case of the small thresholds, the numbers of first order streams of Type A are larger than those of Type E.

3. Analysis of the Variations of Stream Numbers and Length

In this section, we consider the meaning of variations and differences of stream numbers and average stream length that correspond to the change of thresholds. The changes of stream numbers of each order are shown in Fig. 6. All types gradually decrease as thresholds become larger. For Type A and Type E, stream numbers decrease smoothly. The first order streams of Type E decrease rather rapidly than those of Type A as thresholds increase from 0 to 1. This is caused by the variation of D_A which is larger than that of E_L as shown in Fig. 5. Higher order streams of Type A and Type E decrease similarly to the first order streams. For large thresholds of Type A and Type E in the drainage B, the first order streams are steady at approximately 0.3. This is explained by

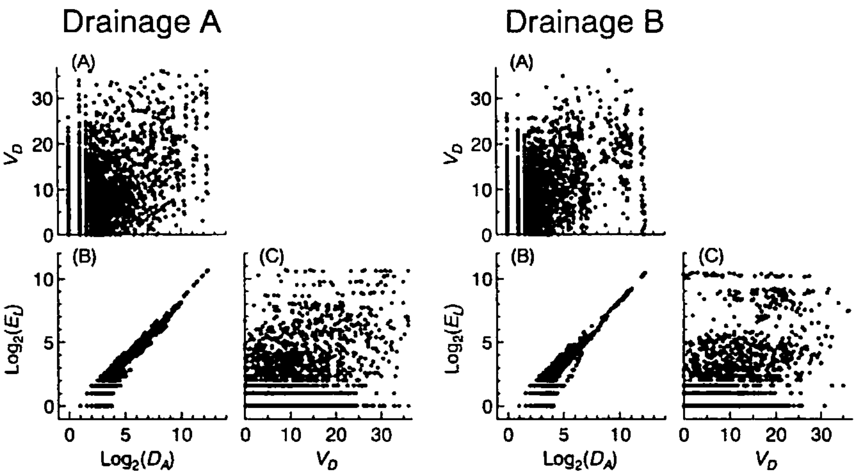

Fig. 5 Scatter diagrams among three criteria
(A) $\log_2(D_A)$ versus V_D, (B) $\log_2(D_A)$ versus $\log_2(E_L)$, (C) V_D versus $\log_2(E_L)$.

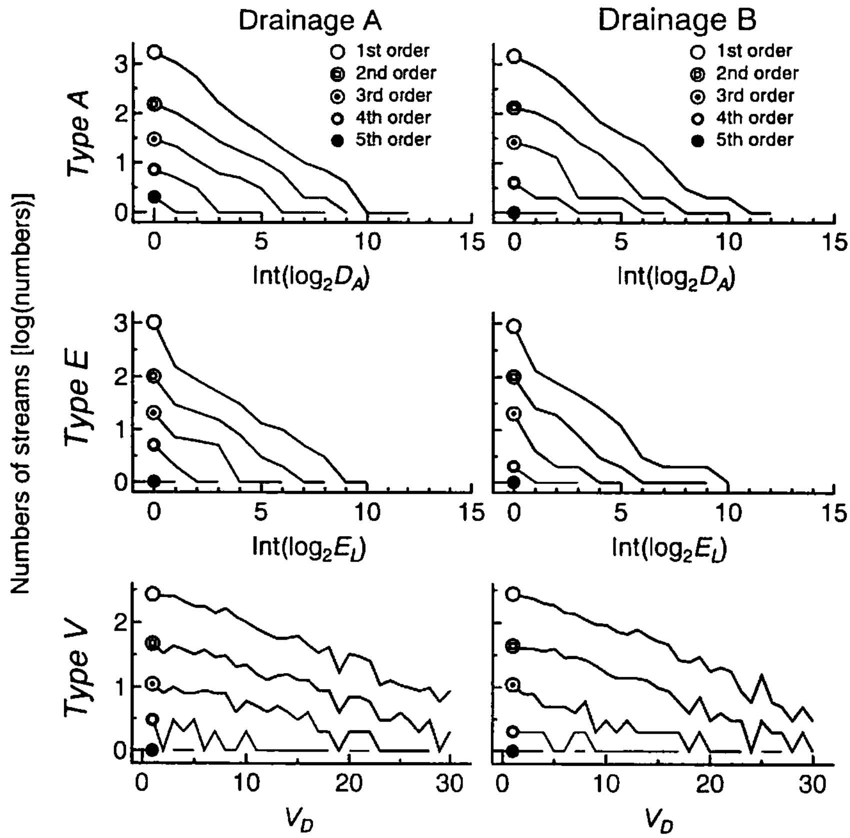

Fig. 6 Changes of stream numbers associated with the variation of three criteria: Diagrams of three drainage network models (Type A, Type E and Type V) of each drainage basin (drainage A and drainage B)
Dot variation indicates stream orders of lines (first to fifth order streams).

a condition that the stream heads are set on upstream or downstream in the same segment relatively. The length of stream decreases but the numbers of streams are steady, even if the threshold becomes large (Fig. 7).

On the contrary, Type V stream networks decrease with some fluctuations. The only local relief can cause the variation of Type V stream numbers. Sudden dips are observed at 10 and 24 of drainage A and B, respectively. These dips are caused by sudden decrease of stream heads at corresponding thresholds. Although there are no evidences to explain these decreases, we consider that the boundaries of local landforms are detected as sudden decreases.

Nogami (1995) mentioned that these three criteria are characterized as local values. D_A and E_L, which are adopted as criteria of Type A and Type E respectively, are successively increasing from upper to down streams. However, V_D is not related to

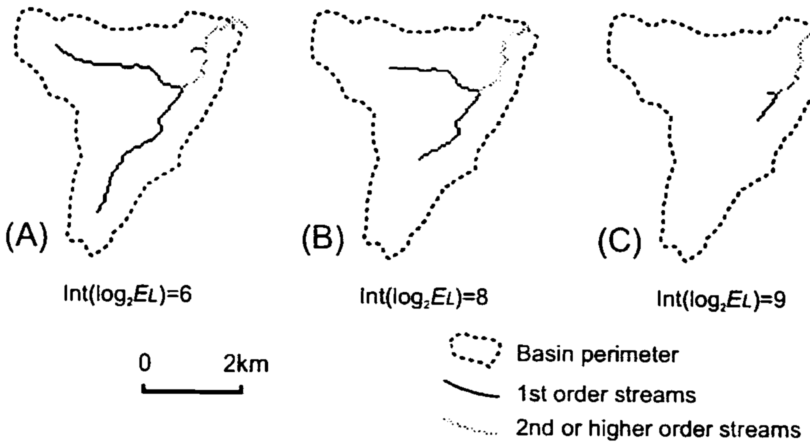

Fig. 7 Increment of threshold and stream shortening, example of drainage B
Dashed lines are basin perimeters, black lines are first order streams and gray lines are second or higher order streams. Threshold of int($\log_2 E_L$) increases as (A) to (C).

neighboring values. This means that V_D is an independent local value.

Figure 8 shows that the changes of average stream length associated with threshold variations. Average stream length of each stream increases as the thresholds become larger. For the drainage B, first order streams of Type A and Type E grow rapidly when D_A is taken from 7 to 8 and L_E is taken from 5 to 6, respectively. There are increases in the drainage A from 6 to 7 in Type A and from 4 to 5 in Type E, though an obvious increase does not appear in the drainage B. This means that the order transitions occur at these thresholds. The order transition is defined as a stream order transition from one stream order to another associated with the change of threshold (Snell and Sivapalan 1994). The process of the order transition is shown in Fig. 9. Numbers of first order streams decrease and unsatisfying threshold streams are dismissed as thresholds increase (Fig. 9-A and D). Thus, average length of first order streams are extended (Fig. 9-B and E). If thresholds become much larger, all of first order streams are completely dismissed. And the transition occurs from the old second order streams to the new first ones (Fig. 9-C and F). Therefore, average length of the first streams is suddenly increased.

For Type V stream networks, the increase of average length has large fluctuations. Order transitions are observed at 18 to 19 of drainage A and at 23 to 24 of drainage B. However, we can recognize that not only the transitions to the higher order streams (Fig. 9-G and H) but also the transitions to the lower ones (Fig. 9-H and I). Since transitions to the lower order streams were not found in Type A and Type E, the transition process of Type V is considered to be different from those of Type A and Type E. This owes to the characteristics of V_D, which was adopted as the criterion of Type V. Valley depth does not successively increase from upstream. Thus, if threshold parameters are "non-successive" parameter, transitions to the lower order streams occur.

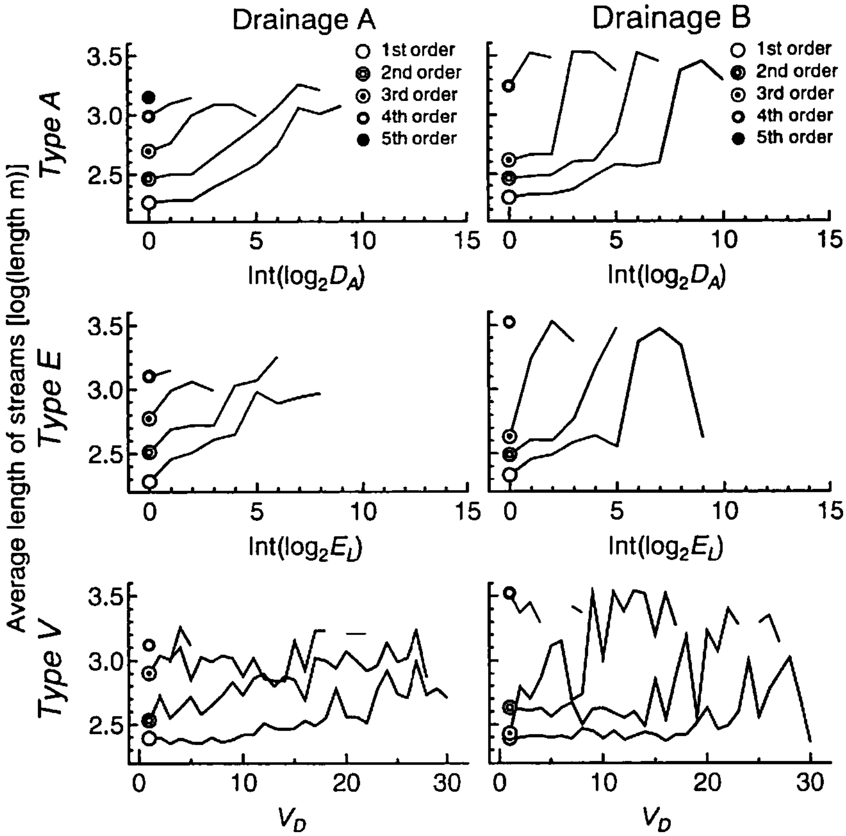

Fig. 8 Changes of average stream length associated with the variation of three criteria: diagrams of three drainage network models (Type A, Type E and Type V) of two drainage basins
Dot variation indicates stream orders of lines (first to fifth order streams).

4. Conclusion

In this article, we examine three types of stream networks (Type A, Type E and Type V) that are established from DEMs and DDMs. These stream types are adopted as thresholds of drainage area (D_A), exterior links (E_L), and valley depth (V_D), respectively. The drainage networks that adopt the former two criteria are extracted from the traditional computer methods. The third one simulates a traditional manual method, which sets stream heads to bending points of contour lines. We calculate stream numbers and average stream length of each order stream, and then consider the variations of numbers and length. Three types of stream networks are characterized by their variations as follows. Type A and Type E stream networks show a smooth decrease in stream numbers and a smooth increase in average stream numbers. D_A and E_L successively increase from upstream to downstream. This causes smooth decrease and increase of the parameters. Thus, these two parameters, D_A and E_L, can be called "successive" parame-

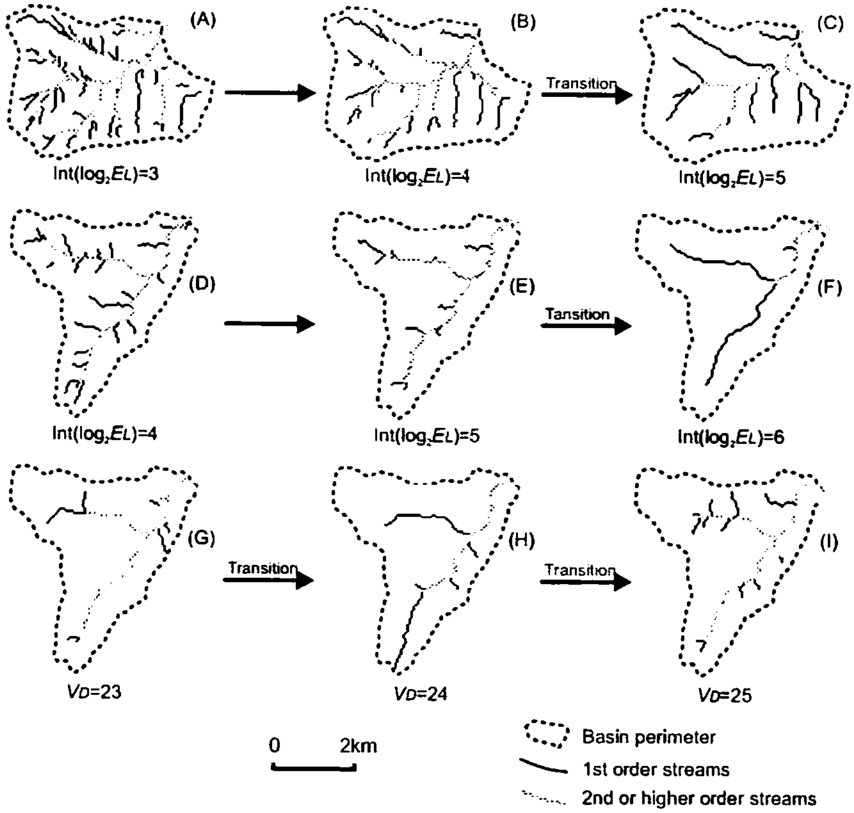

Fig. 9 Examples of order transitions
Dashed lines are basin perimeters, black lines are first order streams and gray lines are second or higher order streams. The upper two rows are examples of single-directional transitions (cases of Type E), lower to higher order streams (B to C and E to F). The lower one is an example of bi-directional transition (a case of Type V). Stream transitions of lower to higher (G to I) and those of higher to lower streams (H to I) occur as threshold becomes large (V_D=23 to 25).

ter. General trends of Type V stream networks decrease in streams numbers and increase in average stream length, which are same as in Type A and Type E. However, Type V has small fluctuations that are caused by the difference of characteristic on V_D that does not successively increase from upstream. That is, V_D is the completely independent "local" and "non-successive" parameters.

These differences between "successive" and "non-successive" parameters cause the differences of order transition styles. Order transitions of "successive" parameters are single-directional such as the lower order to the higher order. However, "non-successive" parameters can cause bi-directional transitions of lower to higher and higher to lower, when thresholds are "successive" parameters. Snell and Sivapalan (1994) have pointed out a concept of "completion" of a stream network. We will examine the difference of stream network completions between "successive" and "non-successive" parameters in further studies.

Acknowledgments

I wish to express my gratitude to Professor Michio Nogami and Dr. Takashi Kumamoto of Graduate School of Tokyo Metropolitan University. Their critical readings of manuscripts and helpful suggestions are very fruitful to this study. For members of LaGIS (Laboratory of Geographic Information Studies), their valuable discussion is very helpful to this study.

References

Helmlinger, K., Kumar, P., and Foufoula-Georgiou, E. 1993. On the use of digital elevation model data for Hortonian and fractal analyses of channel networks. *Water Resour. Res.* 29: 2599-2613.

Horton, R. E. 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. *Geological Society of America Bulletin* 56: 275-370.

Jarvis, R. S. 1972. New measure of the topologic structure of dendritic drainage networks. *Water Resour. Res.* 8: 1265-1271.

Jarvis, R. S. 1976. Classification of nested tributary basins in analysis of drainage basin shape. *Water Resour. Res.* 12: 1151-1164.

Kirkby, M. J. 1993. Network hydrology and geomorphology. In *Channel Network Hydrology*, eds. K. Beven and M. J. Kirkby, 1-11. Chichester: John Wiley & Sons.

Marks, D., Dozier, J., and Frew, J. 1984. Automated basin delineation from digital elevation data. *Geo-processing* 2: 299-311.

Nogami, M. 1991. Advanced application of geographic information, especially raster-type grid maps. *Geoinfomatics* 2: 331-339.*

Nogami, M. 1995. Geomorphometric measures for digital elevation models. *Z. Geomorph., N. F., Suppl.* 101: 53-67

O'Callaghan, J. F. and Mark, D. M. 1984. The extraction of drainage networks from digital elevation data. *Computer Vision, Graphics, and Image Processing* 28: 232-344.

Rigon, R., Rinaldo, A., Rodriguez-Iturbe, I., Bras, R. L., and Ijjasz-Vasquez, E. 1993. Optimal channel networks: a framework for the study of river basin morphology. *Water Resour. Res.* 29: 2599-2613.

Sakaguchi, Y. 1965. Development of a drainage basin and characteristics of the drainage basins of Japan. *Geographical Review of Japan* 38: 18-35.*

Snell, J. and Sivapalan, M. 1994. Threshold effects in geomorphological parameters extracted from DEM's. *Transactions, Japanese Geomorphological Union* 15A: 67-93.

Takayama, S. 1972. Map scale effect on the stream order analysis. *Geographical Review of Japan* 45: 112-119.*

Yoshiyama, A. 1989. Drainage network generation and measurement based on digital elevation data. *Geographical Reports of Tokyo Metropolitan University* 24: 43-53
Yoshiyama, A. 1994. Relationship between channel slopes and topographical parameters of drainage basins. *Geographical Review of Japan* 67A: 794-804.*

(*: in Japanese with English abstract)