CSIS Discussion Paper #56

Drainage density and slope angle in Japanese bare lands from high-resolution DEMs

Zhou LIN [a,*] and Takashi OGUCHI [b]

[a] Department of Earth and Planetary Science, Graduate School of Science, the University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

[b] Center for Spatial Information Science, the University of Tokyo, 4-6-1, Komaba, Meguro-ku, Tokyo 153-8904, Japan

* Corresponding author. E-mail address: lin@csis.u-tokyo.ac.jp (Z. Lin)

Abstract

Relations between drainage density and slope angle for three bare lands in Japan were analyzed with special attention to channels at early erosion stages and channels in a badland-type terrain. The bare lands were caused by either volcanic eruptions or landsliding. Raster digital elevation models (DEMs) with a 1-m resolution and ortho aerial photos were generated using digital photogrammetry to enable detailed stream-net extraction and topographic analyses. Data for drainage density, slope angle and relative height for 88 watersheds were obtained from the DEMs and derived stream-nets. The relation between drainage density and slope angle for each watershed can be divided into two types: downward sloping and convex upward. Although previous studies suggested that drainage density positively correlates with slope angle if overland flow is dominant, such an upward sloping correlation seldom occurs in the study areas. The two types of drainage density - slope angle relations correspond to differing channelization stages that reflect the extension and integration of existing channels as well as the formation of new low-order streams in response to base-level lowering. The location of watersheds within each study area seems to play a major role in determining the stages of channel development and, in turn, the types of density - slope angle relations.

Key words: Stream-nets, Channel development, Digital photogrammetry, Geomorphometry, GIS

Introduction

Drainage density, total stream length per unit area (Horton, 1932, 1945), represents the degree of fluvial dissection. Drainage density is positively correlated with slope angle or relative relief in some regions in the United States (Schumm, 1956; Smith, 1958; Montgomery and Dietrich, 1992), but negatively in Japanese mountains (Mino, 1942; Yatsu, 1950). Oguchi (1997) has attributed the negative correlation to the decline of channel sidewalls on steep slopes related to slope failure. Tailing and Sowter (1999) have summarized previous studies and note drainage density correlates positively with slope angle if overland flow is dominant, but negatively if shallow mass wasting is dominant. Such differences have also been inferred from a three-dimensional landscape evolution model by Tucker and Bras (1998). Howard (1997) has similarly indicated drainage density and slope angle correlate negatively in quickly eroding areas, but positively in slowly eroding areas.

The applicability of these relatively simple summaries, however, needs to be examined carefully. It is still uncertain how the development of drainage systems with time affects the relation between drainage density and slope angle. To solve this problem, channels at different stages of stream-net growth should be surveyed. Although high-resolution topographic data are needed to investigate shallow and narrow channels at early erosion stages, obtaining such information in the field is tedious, and existing topographic maps are often useless because of limited resolution. Instead, analytical and digital photogrammetry can efficiently provide high-resolution topographic data from stereo photographs (Lane et al., 1993; Chandler, 1999).

This study examines drainage density and slope angle for three bare lands in Japan. High-resolution raster digital elevation models (DEMs) were acquired using digital aerial photogrammetry. These bare lands, originally caused by volcanic eruptions or landsliding, include channels at various erosion stages because their eruption/landslide ages as well as local topographic relief are different.

The study areas

The study areas are located in Usu Volcano, Kusatsu-Shirane Volcano, and the Aka-Kuzure Landslide in northern and central Japan (Fig. 1). Usu, a stratovolcano in southwestern Hokkaido, consists mainly of hypersthenes dacite (Kadomura et al., 1988). The studied watershed has an area of 0.18 km^2 and altitudes of 450 to 725 m (Fig. 1, U). The watershed underwent thick deposition of volcanic ash during eruptions between August 1977 and October 1978. The master gully in the central watershed first formed at the late stage of the 1977-1978 eruptions. Then the network of rills and gullies widely extended by the summer of 1979 due to overland flow (Kadomura et al., 1983). Only sparse grass vegetation existed in the study area until the early 1980s.

Kusatsu-Shirane is an active volcano in central Japan. Although it consists mainly of Tertiary andesite, historical eruptions occurred in 1882, 1832, 1942, 1976 and 1982 (Uto et al., 1983). The area studied is located on the eastern slope of the main volcanic cone with a crater lake (Fig.1, K). It has an area of 0.19 km^2 and altitudes of 1,900 to 2,200 m, and was subjected to ash fall during the historical eruptions. Gully erosion by overland flow has been dominant, and only grass vegetation occurs in the study area.

Aka-Kuzure is a large landslide in the Southern Japanese Alps, forming a steep watershed with an area of 0.43 km^2 and altitudes of 1,800 to 2,000 m (Fig.1, A). The watershed is underlain by sandstone, shale, and their alternations (Chigira and Kiho, 1994). The formation age of the landslide is unknown, but it has existed since at least one hundred years ago. The surface of the landslide is finely dissected and almost devoid of vegetation, showing a badland-type landscape. Shallow slope failure and subsequent sediment removal by running water are major hillslope processes.

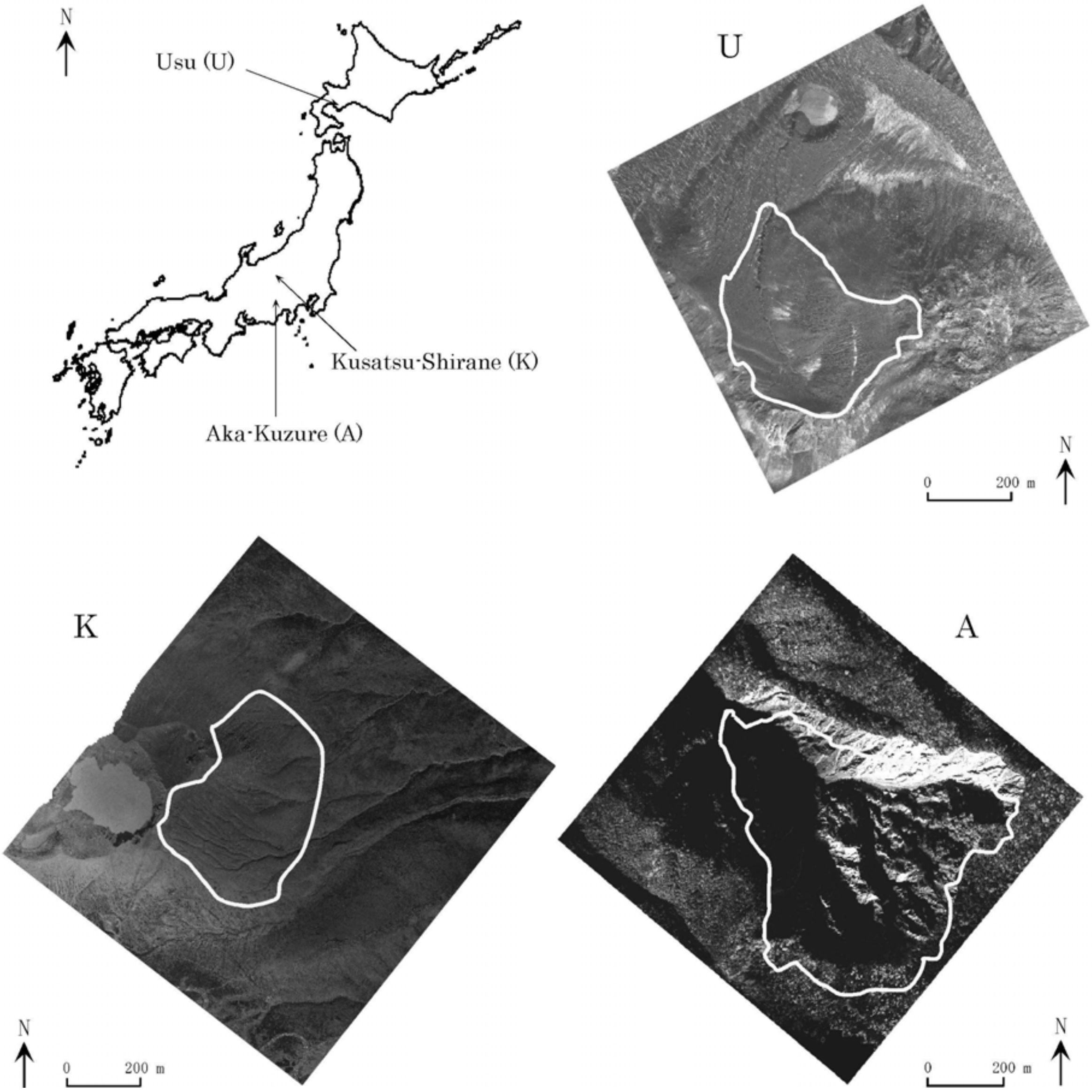

Fig. 1 Locations and orthophotos of three study areas.

Data

Stream-nets DEMs and orthophotos

Digital photogrammetry was applied to 1:8,000 vertical airphotos to produce 1-m DEMs for the three areas. The periods of the airphotos are October 1979 for Usu, August 1985 for Kusatsu-Shirane, and October 1995 for Aka-Kuzure (Table 1). Previous studies (Powers et al., 1996; Derose et al., 1998; Brown and Arbogast, 1999; Lane et al., 2000; Westaway et al., 2000) have suggested that DEMs with a grid interval of 1 m can be produced from 1:8,000 airphotos, and the DEM grid interval should be at least 5 to 10 times as large as the pixel spacing of scanned images (Pyle et al., 1997; Butler et al., 1998; Lane, 2000). Therefore, the positive films of the airphotos were scanned into raster images with a 20-μm resolution or a pixel dimension of 0.162 m using Leica DSW500, a high-quality photogrammetric scanner. Then 1-m DEMs for Usu and Kusatsu-Shirane were generated using the VirtuoZo DPW (Digital Photogrammetric Workstation) at Center for Spatial Information Science, the University Tokyo. The 1-m DEM for Aka-Kuzure was also generated using the Leica-Helava DPW at Tamano Consultant Co. Ltd., Nagoya, Japan. First, interior, relative and absolute orientations were undertaken to restore the internal geometry of cameras, establish the geometric relationship of stereo-pairs, and provide shifted photographic models. Then 1-m DEMs and orthophotos (Fig. 1) were generated using the obtained models.

Table 1 Airphotos used for digital photogrammetry and RMSE values at GCPs.

Area	Airphotos (1:8,000)				DEM Errors			
	Period	Camera	Frame number	GCP number	Model	X	Y	Z
Usu	Oct 1979	153.12 mm RC-10	3	10	1	0.1522	1.0026	0.0451
					2	1.2196	1.6909	0.3517
Kusatsu-Shirane	Aug 1985	152.56 mm RC-10	4	15	1	0.9506	1.1197	0.6611
					2	0.9648	0.2896	0.6884
					3	0.5657	1.0347	0.4239
Aka-Kuzure	Oct 1995	152.95 mm RC-10	2	5	1	1.9991	1.8387	0.7818

The quality of the constructed DEMs looks sufficient for general topographic analysis. RMSE values showing errors at ground control points (GCPs) are smaller than 2 m in X and Y directions and 0.8 m in a Z direction (Table 1), which are comparable to those reported in other digital photogrammetric studies using medium-scale airphotos (Derose et al., 1998; Brown and Arbogast, 1999). The shaded relief images generated from the DEMs also clearly depict detailed topographic features such as distribution of small channels and ridges. However, small unnatural straight cliffs occur in Usu and Kusatsu-Shirane where DEMs derived from different stereo pairs were merged. To remove the artifact, a smoothing filter was applied to narrow zones along the cliffs.

Stream-nets

Stream-nets for the three study areas were delineated using the 1-m DEMs and orthophotos. DEMs permit the automatic extraction of stream-nets (e.g., Mark, 1984; Martz and Garbrecht, 1992), and the most common method, which is often implemented to major commercial GIS software, assumes a minimum contributing area to determine channel-head locations. However, minimum contributing areas should vary even within a small watershed according to local factors such as topography and lithology (e.g., Tucker et al., 2001; Vogt et al., 2003). To solve this problem for Usu and Kusatsu-Shirane, we determined the location of each channel head by visual interpretation of the orthophotos. Stream-nets were also automatically extracted from the 1-m DEMs based on the threshold contributing-area method of Jenson and Domingue (1988). The threshold area was set to be small to delineate both major and subtle valley lines. Then the delineated streams above the visually determined channel heads were deleted. The final stream nets (Fig. 2a, U and K) are consistent with both the DEMs and actual channel-head locations.

Although channel heads in Usu and Kusatsu-Shirane are topographically well-defined, those in Aka-Kuzure are indistinct because of badland-type topography, requiring another definition of stream-nets. We first assumed that a first order stream starts from a ridge, because channels in Aka-Kuzure usually attain ridges due to widespread mass wasting. Then we allocated stream orders to all the DEM cells following Strahler (1952), i.e., the stream order increases when streams of the same order meet (Fig. 3). We developed a macro program for ArcView for this stream-ordering. When cells equal to or higher than the fourth order are regarded as streams and the other cells are as interfluves, mean drainage density for Aka-Kuzure becomes closest to that for Usu and Kusatsu-Shirane. Thus, the fourth and higher-order streams were regarded as the elements of stream-nets in Aka-Kuzure (Fig 2a, A).

Sub-watersheds

To examine stream-net properties in relation to local topographic variations, sub-watersheds within each study area were delineated using the DEMs. Both the area of each sub-watershed and the total number of the watersheds should be adequately large for statistically meaningful analyses. Thus, we delineated 20 second-order sub-watersheds in Usu (designated as U01 to U20), 14 second-order sub-watersheds in Kusatsu-Shirane (K01 to K14), and 54 sixth-order sub-watersheds in Aka-Kuzure (A01 to A54) (Fig. 2b). The area of the sub-watersheds ranges from ca. 1,200 to 11,600 m^2 for Usu, 4,900 to 11,800 m^2 for Kusatsu-Shirane, and 2,200 to 5,600 m^2 for Aka-Kuzure. Each sub-watershed was further divided into 10 m * 10 m raster grid cells.

Morphometric parameters

The total length of channels in each sub-watershed was computed using our original C++ algorithm to derive drainage density. One of four channel lengths, 0 m, 1 m, 1.21 m, and 1.41 m, was allocated to each grid cell based on the occurrence of channels in neighboring cells (Fig. 4). The calculated drainage density for each sub-watershed ranges from 0.02 to 0.11 m/m^2 for Usu, 0.03 to 0.06 m/m^2 for Kusatsu-Shirane, and 0.04 to 0.14 m/m^2 for Aka-Kuzure. Drainage density for each 10 m * 10 m cell within a sub-watershed was also computed.

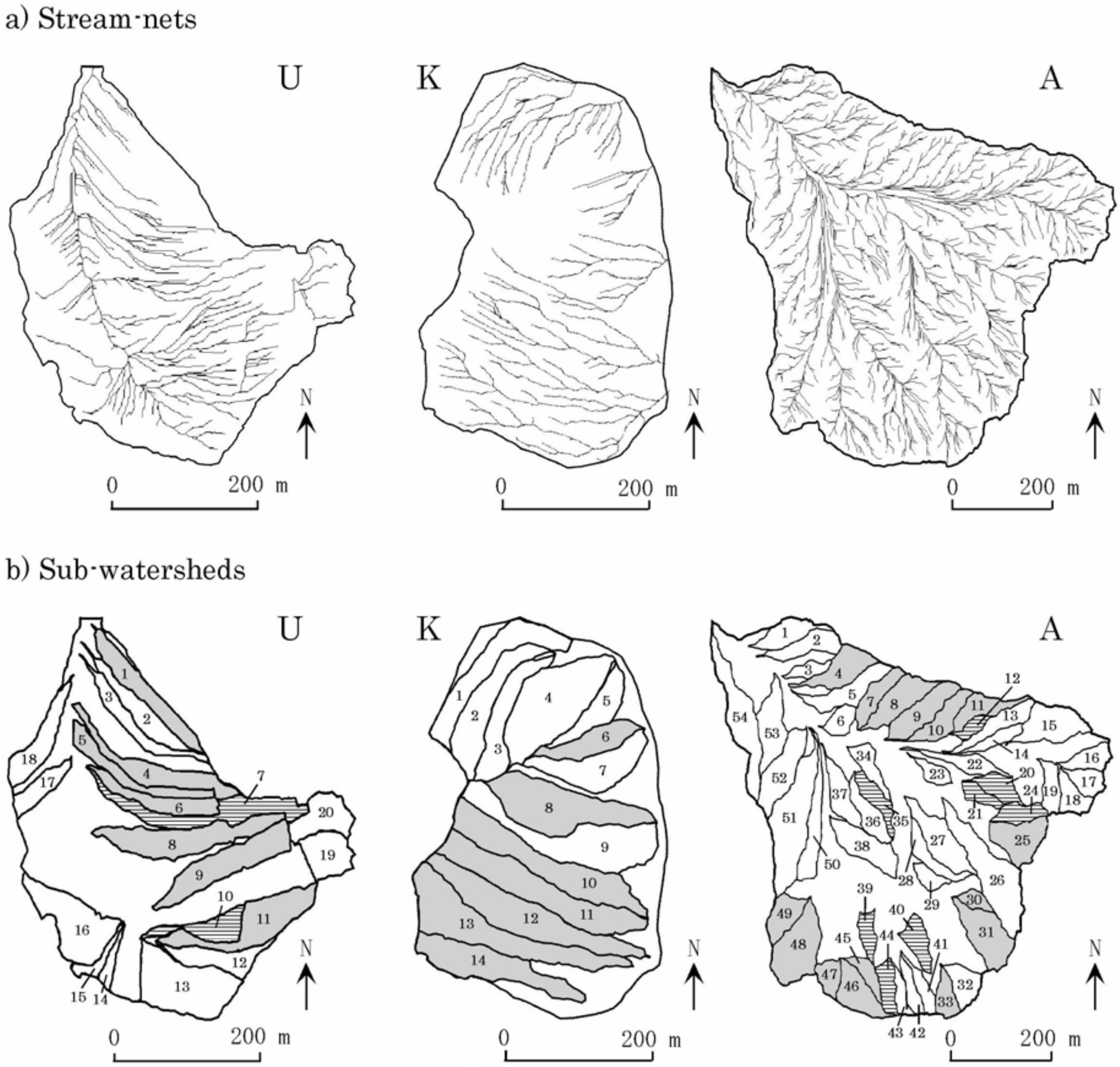

Fig. 2 (a) Stream-nets and (b) sub-watersheds in Usu (U), Kusatsu-Shirane (K) and Aka-Kuzure (A). White watersheds: Type 1, gray watersheds: Type 2, hatched watersheds: non-classified.

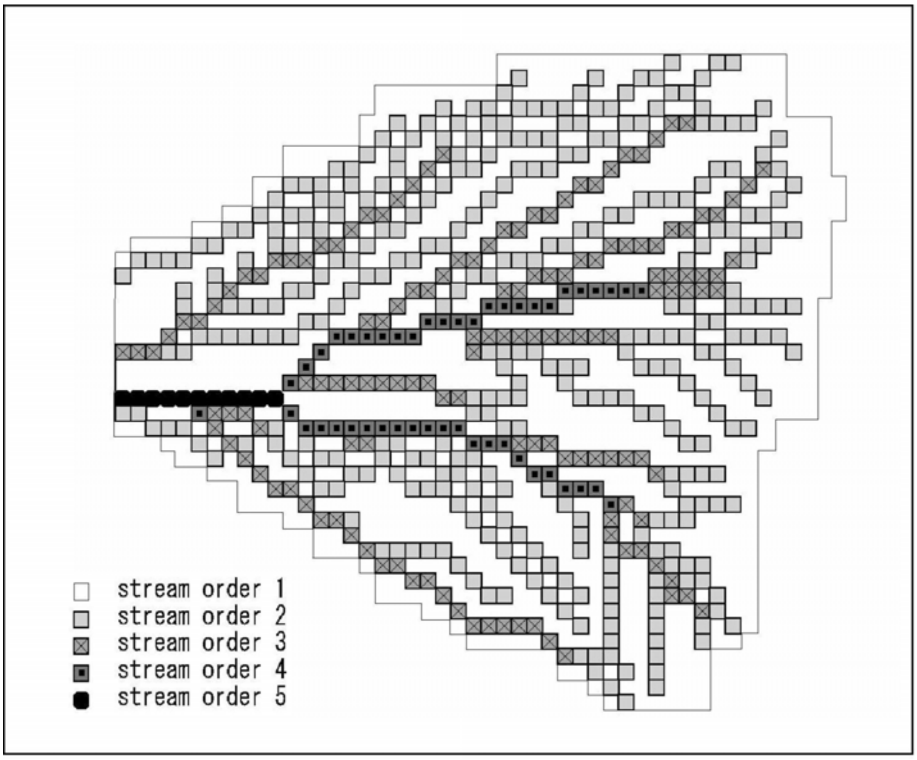

Fig. 3 Part of stream-nets in Aka-Kuzure with badland-type topography without distinct channel heads.

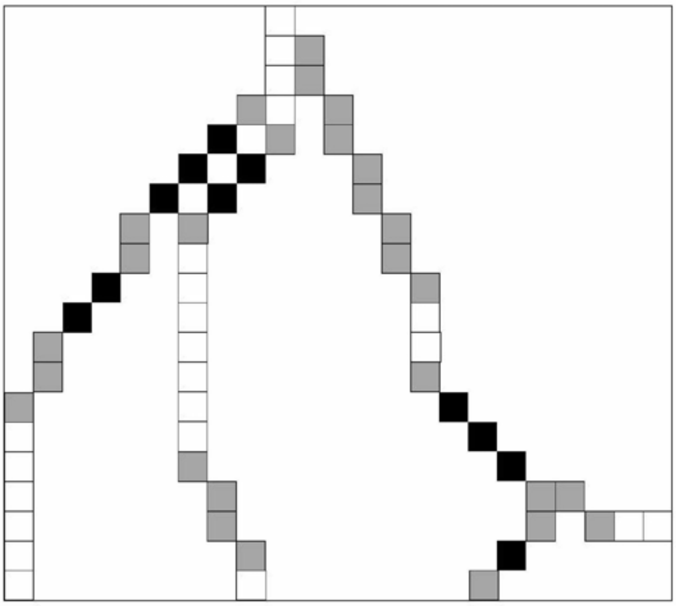

Fig. 4 Stream lengths for grid cells. White squares: 1 m, gray squares: 1.21 m, black squares: 1.41 m, non-squared cells: 0 m.

The slope angle for each DEM cell was calculated from elevations at eight neighboring cells, based on the method by Jenson and Domingue (1988). Then the mean slope angle for each sub-watershed and in a 10 m * 10 m cell was computed. The mean slope angle for each watershed is 15 to 24 degrees for Usu, 18 to 28 degrees for Kusatsu-Shirane, and 43 to 57 degrees for Aka-Kuzure.

Relative height (H_r) is defined to express the relative location of a 10 m * 10 m cell within a sub-watershed:

$$H_r = \frac{H - H_{\min}}{H_{\max} - H_{\min}}$$

where H is the mean height of a 10 m * 10 m area, $H_{\min}$ is the minimum height of a sub-watershed, and $H_{\max}$ is the maximum height of a sub-watershed. The relative height varies from 0 (bottom) to 1 (top).

Data analysis

Slope angle and drainage density

The relation between slope angle and drainage density was examined for each sub-watershed. Using data for the 10 m * 10 m grid cells within a sub-watershed, mean drainage density for each 2-degree slope bin was computed and plotted against slope angle. Then the quadratic equation was fitted to approximate the relation between slope angle and drainage density for each watershed. Figure 5 shows six examples of the plots with the fitted trend lines. Their trends can be divided into two types: downward sloping showing that drainage density tends to decrease with increasing slope angle (Type 1), and convex upward showing that drainage density tends to increase with slope angle for smaller slope angles but decrease for larger slope angles (Type 2). The relations for the other 82 watersheds can also be classified into the two types (Fig. 6) except two in Usu (U-07 and U-10) and eight in Aka-Kuzure (A-12, 20, 21, 24, 35, 39, 40, 44) with various other relations. The trend lines for Type 1 are mostly concave upward (Fig. 6).

Figure 7 is a plot of mean slope angle and mean drainage density for each sub-watershed classified according to Types 1 and 2. The two types in Usu are clearly separated since Type 1 has lower drainage density than Type 2. Conversely, some Type 1 watersheds in Aka-Kuzure tend to have higher drainage density than Type 2, since most watersheds with drainage density higher than 0.08 m/m^2 belong to Type 1. Such differences between the two types are indistinct in Kusatsu-Shirane.

Distribution of watershed types

The Type 1 and Type 2 sub-watersheds tend to have different types of spatial distributions (Fig. 2b). Most Type 1 watersheds in Usu are located in the peripheral area, whereas the Type 2 watersheds are located mainly in the central area. Most Type 1 watersheds in Kusatsu-Shirane occur in the northern part, but most Type 2 watersheds occur in the southern part. The Type 1 watersheds in Aka-Kuzure take place in various parts of the landslide including the central area, whereas the Type 2 watersheds are located only in the periphery.

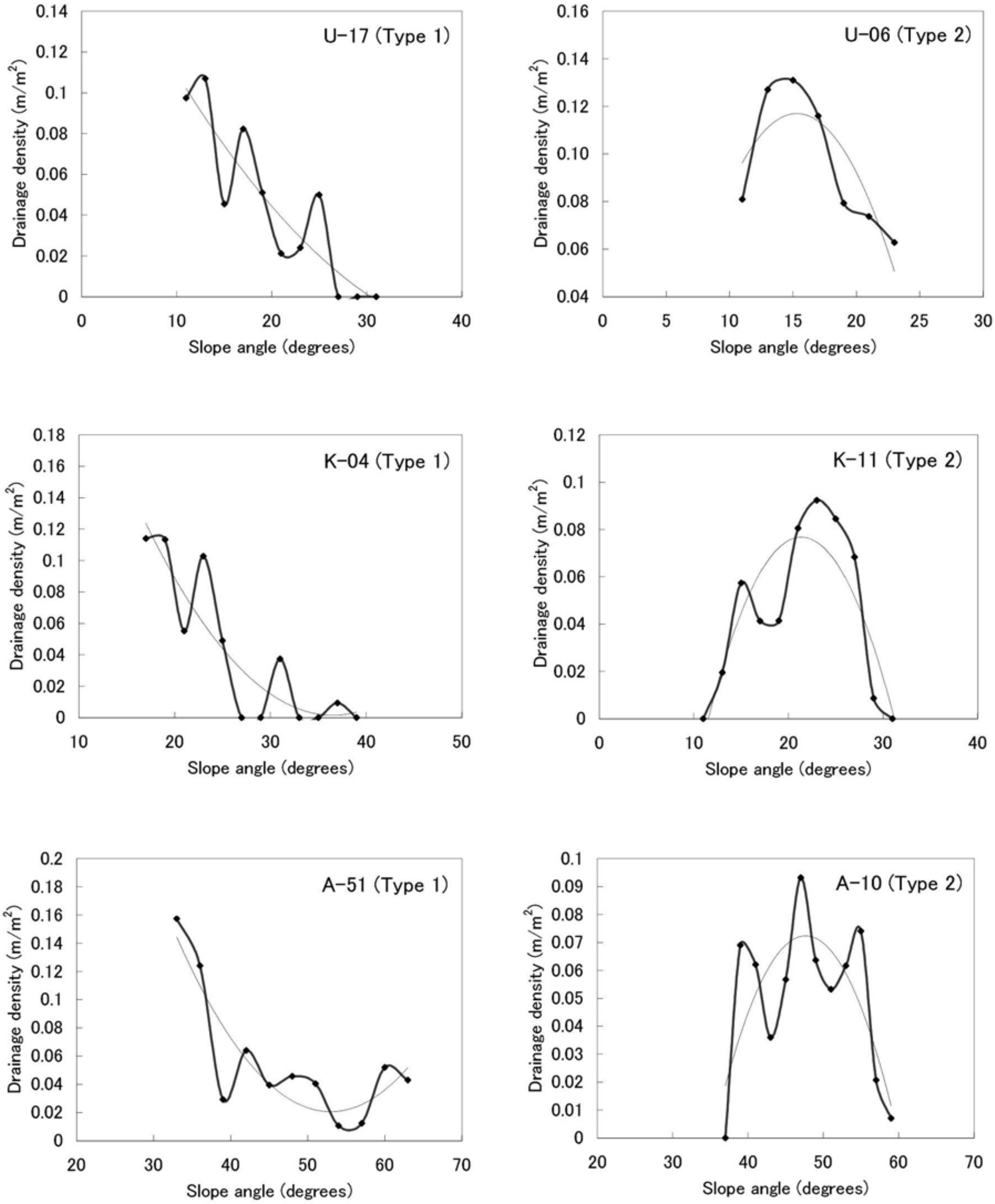

Fig. 5 Examples of two types of drainage density - slope angle relations. Dashed lines show approximation by quadratic equations. Type 1 is downward sloping (and concave). Type 2 is convex.

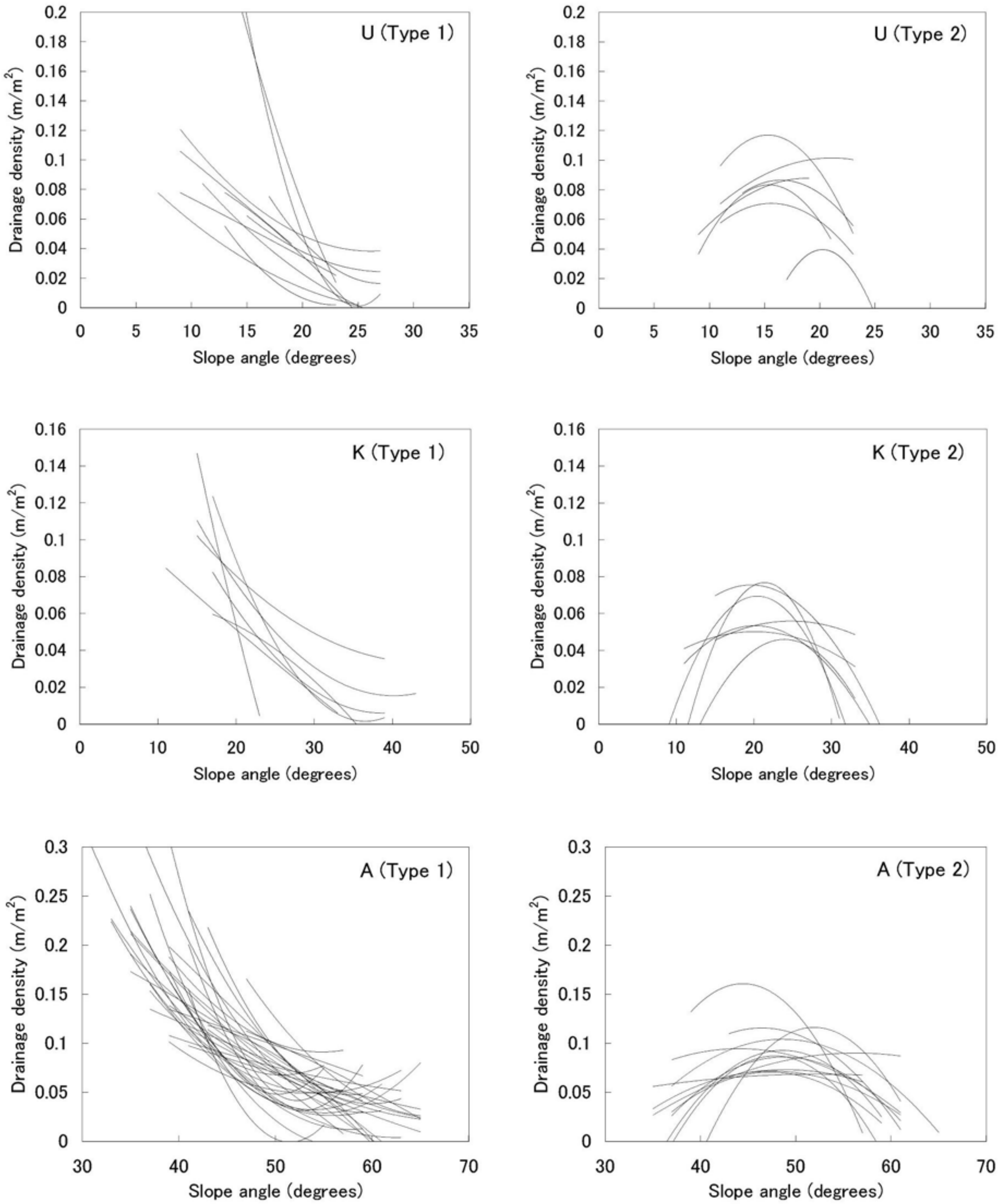

Fig. 6 Trend lines of two types of drainage density - slope angle relations. U: Usu, K: Kusatsu-Shirane, A: Aka-Kuzure.

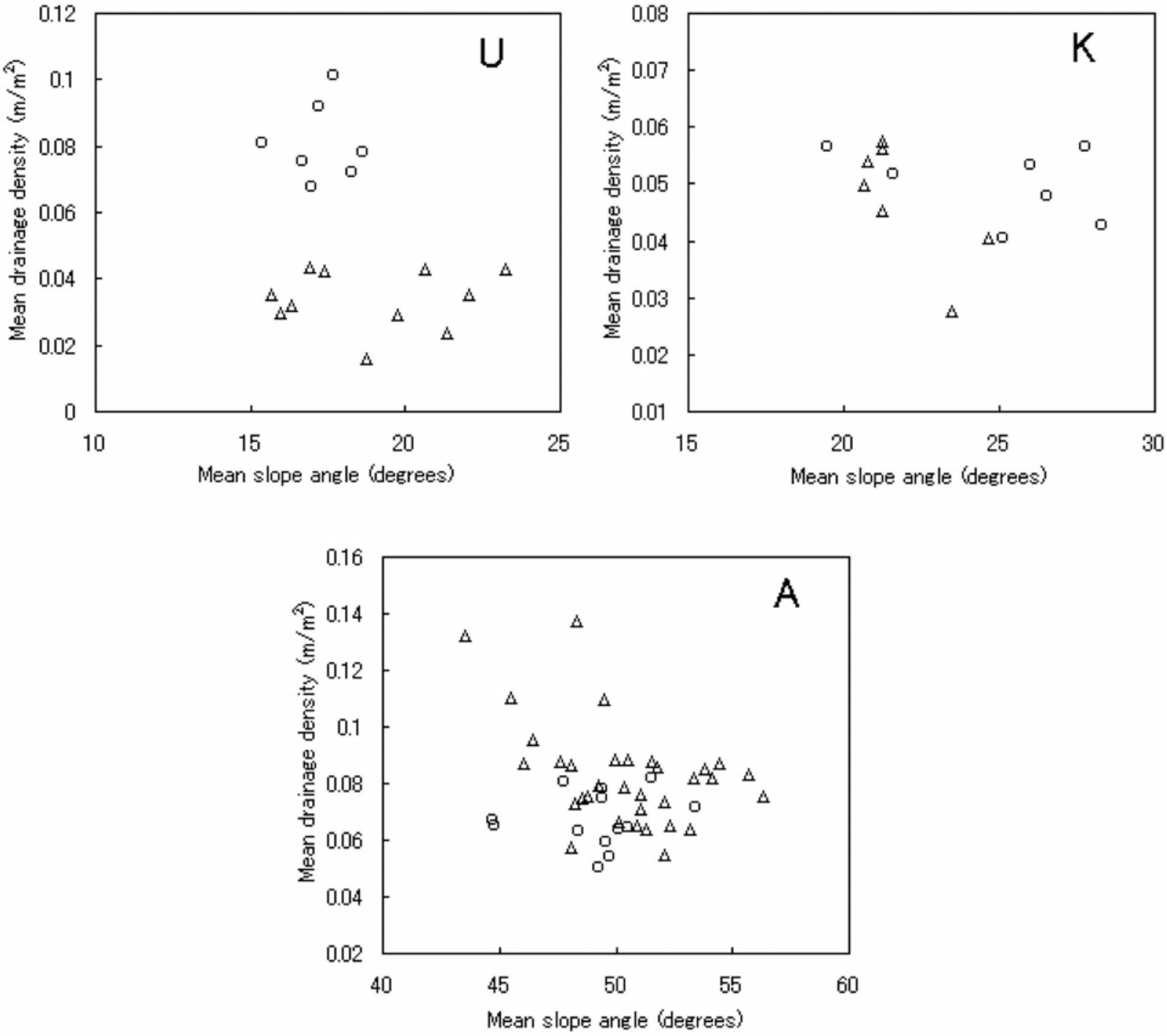

Fig. 7 Plot of mean drainage density and mean slope angle for each watershed. U: Usu, K: Kusatsu-Shirane, A: Aka-Kuzure. Triangles: Type 1, Circles: Type 2.

Stream-net structure

Basic Horton's parameters representing stream-net structure were calculated for Type 1 and Type 2 in each study area, based on the total number and the mean length of channels belonging to each stream order (Table 2). In Usu and Kusatsu-Shirane, Type 2 has larger bifurcation ratios and stream-length ratios than Type 1. In Aka-Kuzure, by contrast, Type 2 has smaller bifurcation ratios and stream-length ratios than Type 1.

Table 2 Parameters of stream-net structure for three study areas. Note the method of stream ordering for Aka-Kuzure differs from that for Usu and Kusatsu-Shirane.

Area	Type	Stream order	Stream number	Bifurcation ratio	Mean stream length	Stream length ratio
Usu	1	1	39	3.54	38.8	1.30
		2	11		50.5	
	2	1	37	5.28	63.4	1.74
		2	7		110.7	
Kusatsu-Shirane	1	1	34	4.85	50.8	2.56
		2	7		130.5	
	2	1	40	5.70	57.1	3.41
		2	7		194.3	
Aka-Kuzure	1	4	486	4.76	14.0	2.38
		5	102	3.09	33.3	2.52
		6	33		84.0	
	2	4	160	4.10	17.7	1.77
		5	39	3.00	31.4	2.46
		6	13		77.4	

Relative height and drainage density

The relation between relative height and drainage density for each sub-watershed was also examined. Relative height was divided into 10 bins with a 0.1 interval. Using the 10 * 10 m grid cell data within a watershed, mean drainage density for each bin was computed and plotted against slope angle, and the quadratic equation was fitted to their relations. Figure 8 shows six examples of the plots, and Fig. 9 shows the approximated trend lines for all the Type 1 and Type 2 watersheds. Types 1 and 2 in Usu and Kusatsu-Shirane also differ in the relation between drainage density and relative height, in that the lines for Type 1 are mostly downward sloping and concave upward, while those for Type 2 is convex upward (Fig. 9). In other words, drainage density - slope angle relations and drainage density - relative height relations tend to have similar trends. Such correspondences also hold true for Aka-Kuzure, although the concavity of Type 2 is less marked, and more exceptions can be found (Fig. 9).

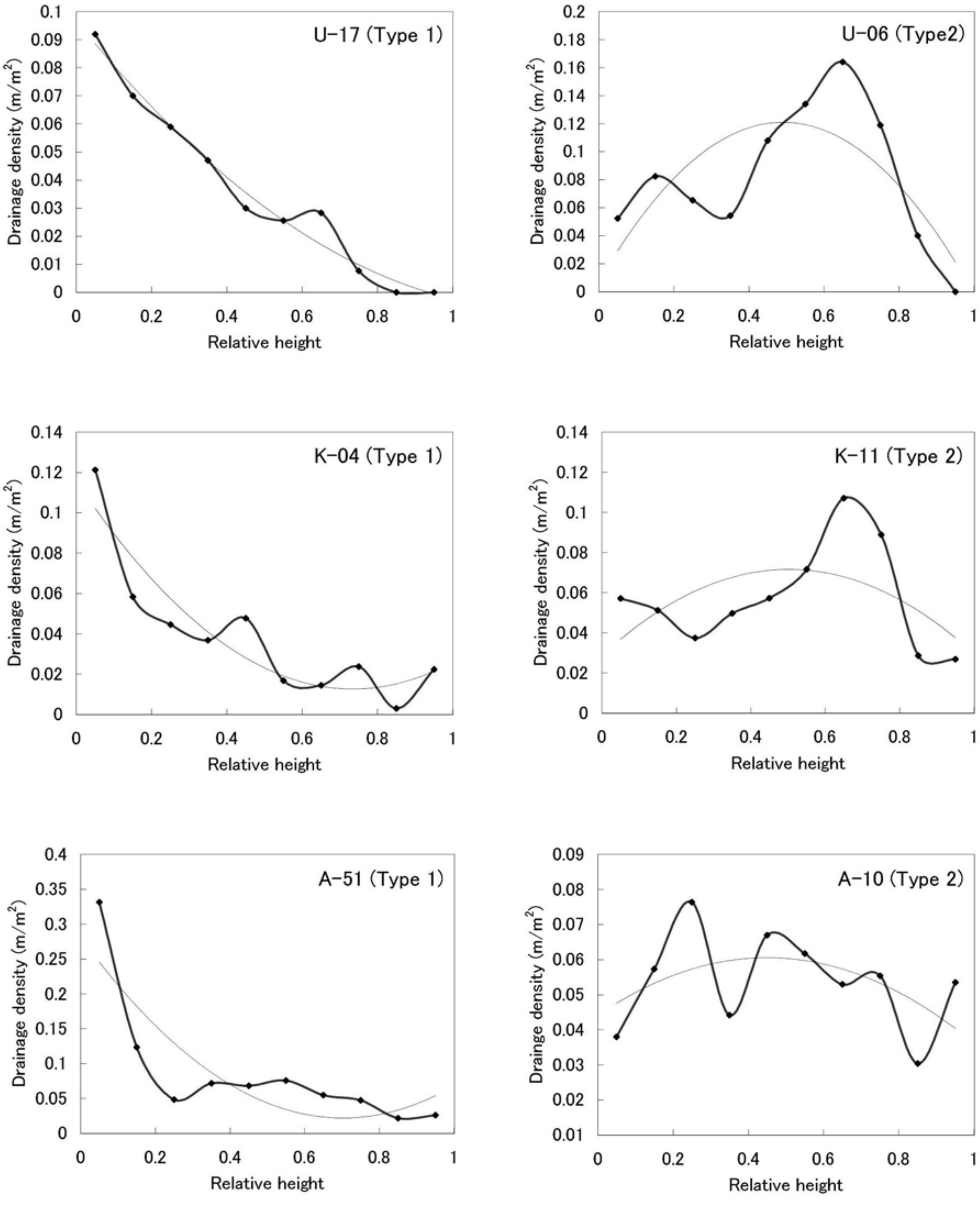

Fig. 8 Examples of drainage density - relative height relations. Dashed lines show approximation by quadratic equations. Type 1 and Type 2 are determined based on drainage density - slope angle relations (see Figs. 5 and 6).

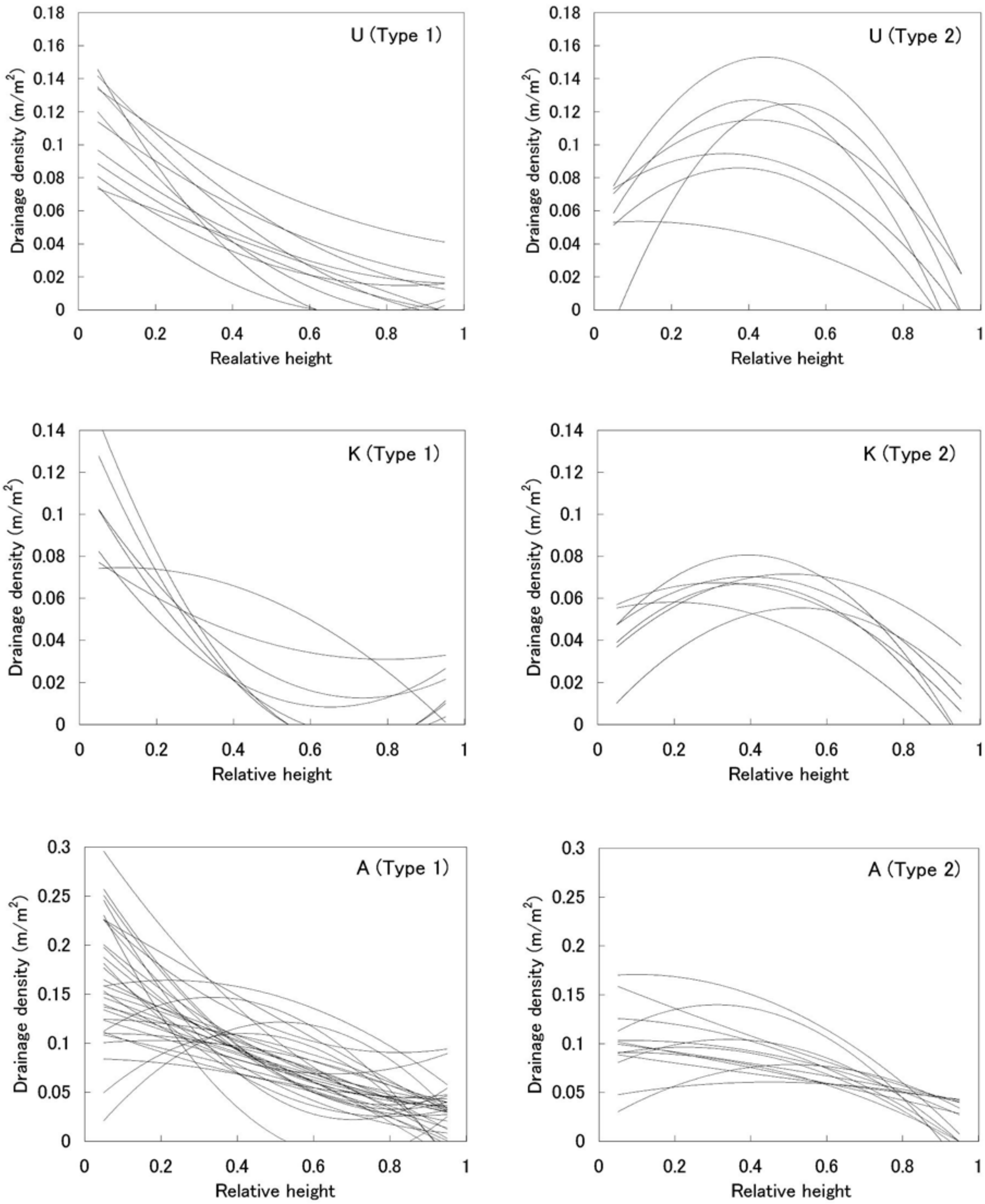

Fig. 9 Trend lines showing drainage density - relative height relations, classified according to types of drainage density - slope angle relations. U: Usu, K: Kusatsu-Shirane, A: Aka-Kuzure.

Discussion

Usu area

Geomorphometric differences between Types 1 and 2 in Usu indicate they are at the different stages of drainage evolution. Lower drainage density, a lower bifurcation ratio, and smaller mean stream lengths for Type 1 (Fig. 7, Table 2) show stream-nets in the Type 1 watersheds are more immature than those in the Type 2 watersheds. The biggest difference is observed in the middle height of each watershed: drainage density at a relative height of 0.5 is around 0.05 for Type 1, but around 0.11 for Type 2 (Fig. 9). Drainage density of Type 1 for medium slope angles (15 to 20 degrees) also tends to be lower than that of Type 2 (Fig. 6). These observations support the inference that Type 1 corresponds to earlier channelization stages, since channel extension usually starts at lower flat areas and subsequently proceeds to higher steeper areas. The change in drainage density - slope angle relations from Type 1 to Type 2 can be accounted for by the enhanced channelization in the middle to upper watershed as erosion progresses. Drainage density for the lower part of the Type 1 watersheds is slightly higher than that of Type 2, which may reflect channel integration with time.

Such differences in the stage of stream-net growth seem to reflect watershed locations. Most Type 2 watersheds in Usu are close to the master gully, and thus have reached more advanced channelization stages than the Type 1 watersheds in the periphery.

Kusatsu-Shirane area

The Type 1 and Type 2 watersheds in Kusatsu-Shirane have topographic differences similar to those in Usu, in that Type 1 has a smaller bifurcation ratio, smaller mean stream lengths, and lower drainage density at the middle height of a watershed (Table 2, Fig. 9), suggesting that Type 2 is at more advanced channelization stages. Unlike Usu, mean drainage density does not differ according to the types (Fig. 7). The drainage density for the lowest part of the Type 1 watersheds (relative height = 0.05) is higher than 0.07, whereas that of Type 2 is lower than 0.06 (Fig. 9), which compensates lower drainage density for the middle height of the Type 1 watersheds. Drainage density for low slope angles (< 20 degrees) of Type 1 is apparently higher than that of Type 2 (Fig. 6). Therefore, marked stream integration seems to have occurred at the lower and flatter areas of the Type 2 watersheds. Moreover, the Type 2 watersheds are located in the southern area where incision by master gullies is more evident than the northern area (Fig. 1). These observations confirm that Type 2 is at advanced channelization stages with integrated channels in the lower gentler areas and extended channels in the higher and steeper areas. Consequently, the two types of drainage density - slope angle relations for Kusatsu-Shirane are also ascribable to different stages of stream-net growth.

Aka-Kuzure area

Unlike the other two areas, it seems inappropriate to assume that Type 2 in Aka-Kuzure corresponds to more advanced channelization stages than Type 1. Although the trend lines of drainage density - relative relief relations for Types 1 and 2 in Aka-Kuzure differ in the same manner as those in the other two areas

(Fig. 9), Type 1 has larger bifurcation ratios and stream length ratios than Type 2, which is reverse to the other two areas (Table 2). The order of mean drainage density for the two types is also reverse to that for Usu (Fig. 7), suggesting that Type 1 represents more advanced channelization.

Type 1 is characterized by relatively short, abundant lower-order streams (Table 2) and widespread channelization dominates at the lower parts of watersheds (Fig. 9), which can be related to base-level lowering at the bottom of the landslide. The topography of a small alluvial fan immediately below the Aka-Kuzure landslide indicates that the stream flowing from the landslide have undergone rapid downcutting in recent years, resulting in the degradation of major tributaries and subsequent slope failure and the creation of new low-order streams because of hillslope instability. It can be assumed that such processes have been more enhanced in the Type 1 watersheds than Type 2, especially in the lower and flatter parts of the watersheds adjacent to the major streams. This assumption conforms to the peripheral distribution of the Type 2 watersheds and their smaller mean slope angles (Figs. 2 and 7), because hillslope incision in response to base-level lowering should be limited in gentle terrains apart from the master stream.

Factors affecting drainage density - slope angle relations

The detailed analysis of stream-net structure and watershed geomorphometry for the three areas has provided fresh insights into drainage density - slope angle relations. Although previous studies suggest that slope angle and drainage density correlate positively if overland flow promotes erosion, such positive correlations seldom occur in Usu and Kusatsu-Shirane where overland flow is dominant. Previous studies also suggest slope angle and drainage density correlate negatively if shallow mass-wasting is dominant, which conforms to the fact that Type 1 often occurs in Aka-Kuzure where slope failure is widespread. However, the common occurrence of Type 2 in all the three areas indicates more attention should be paid to such non-linear relations between drainage density and slope angle. Differences in Types 1 and 2 most likely reflect differing stages of channel development, which often corresponds to the location of sub-watersheds. In Usu and Kusatsu-Shirane, drainage density - slope angle relations shift from Type 1 to Type 2 with the progress of channelization stages owing to channel extension in the middle parts of sub-watersheds and channel integration in the lower parts. In Aka-Kuzure, however, formation of new channels in response to base-level lowering has led to shift from Type 2 to Type 1. In summary, the advance of channelization stages can lead to bi-directional changes between the two types of drainage density - slope angle relations.

Conclusions

Digital aerial photogrammetry was applied to the Usu, Kusatsu-Shirane, and Aka-Kuzure areas in Japan for detailed topographic analyses of channels and surrounding hillslopes using 1-m DEMs. Special attention was paid to relatively new channels at early erosional stages as well as channels in badland-type topography. Stream-nets were obtained based on the two approaches: DEM-based automatic extraction and visual identification of channel heads using ortho-airphotos. Drainage density was analyzed in relation to slope angle and relative height within sub-watersheds.

Although previous studies suggested that the relation between slope angle and drainage density corresponds to dominant erosion types, this study has indicated that they correspond more directly to the stages of channelization. Change in slope angle - drainage density relations with the progress of channelization depends on the current major channelization processes such as the extension and integration of existing channels as well as the formation of new low-order streams in response to base-level lowering.

This paper suggests simple summaries concerning drainage density - slope angle relations have only limited applicability, and careful analyses using high-resolution quantitative data are necessary to discuss the details of the issue. Although this study on the three locations in Japan has provided some new insights, different conclusions may be reached elsewhere, since fluvial and hillslope processes are highly variable according to regional and local factors. Therefore, channelized watersheds in various parts of the world should be investigated in future for better understanding of topographic effects on channel distribution.

Acknowledgements

We thank Mr. S. Sano, Tamano Consultant Co. Ltd., for his support with the construction of the DEM for the Aka-Kuzure area, and Prof. R. Shibasaki and Prof. Z. Shi, University of Tokyo, for allowing us to use the digital photogrammetric workstation in their laboratory. Thanks are also due to Prof. Thad Wasklewicz, University of Memphis, for his constructive review of an early draft of this paper.

References

Brown, D.G., Arbogast, A.F., 1999. Digital photogrammetric change analysis as applied to active coastal dunes in Michigan. Photogrammetric Engineering and Remote Sensing 65, 467-474.

Butler, J.B., Lane, S.N., Chandler, J.H., 1998. Assessment of DEM quality for characterizing surface roughness using close range digital photogrammetry. Photogrammetric Record 16, 271-291.

Chandler, J., 1999. Effective application of automated digital photogrammetry for geomorphological research. Earth Surface Processes and Landforms 24, 51-63.

Chigira, M., Kiho, K., 1994. Deep-seated rockslide-avalanches proceeded by mass rock creep of sedimentary rocks in the Akaishi Mountains, central Japan. Engineering Geology 38, 221-230.

Derose, R.C., Gomez, B., Marden, M., Trustrum, N.A., 1998. Gully erosion in Mangatu Forest, New Zealand, estimated from digital elevation models. Earth Surface Processes and Landforms 23, 1045-1053.

Horton, R.E., 1932. Drainage basin characteristics. Transactions American Geophysics Union 13, 350-361.

Horton, R.E., 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. Bulletin of the Geological Society of America 56, 275-375.

Howard, A.D., 1997. Badland morphology and evolution: interpretation using a simulation model. Earth Surface Processes and Landforms 22, 211-227.

Jenson S.K., Domingue J.O., 1988. Extracting topographic structure from digital elevation data for geographic information system analysis. Photogrammetric Engineering and Remote Sensing 54, 1593-1600.

Kadomura, H., Imagawa, T., Yamamoto, H., 1983. Eruption-induced rapid erosion and mass movements on Usu Volcano, Hokkaido. Zeitschrift für Geomorphologic N. F., Suppl. Bd 46, 123-142.

Kadomura, H., Okada, H., Sintani, T., 1988. 1977-82 volcanism and environmental hazards of Usu Volcano. Hokkaido University Press, 257 pp.

Lane, S.N., 2000. The measurement of river channel morphology using digital photogrammetry. Photogrammetric Record 16, 937-961.

Lane, S.N., Richards, K.S., Chandler, J.H., 1993. Developments in photogrammetry: the geomorphological potential. Progress in Physical Geography 17, 306-328.

Lane, S.N., James, T.D., Crowell, M.D., 2000. Application of digital photogrammetry to complex topography for geomorphological research. Photogrammetric Record 16, 793-821.

Mark D.M., 1984. Automatic detection of drainage networks from digital elevation models. Cartographica 21, 168-178.

Martz L.W., Garbrecht J., 1992. Numerical definition of drainage network and subcatchment areas from digital elevation models. Earth Surface Processes and Landforms 18, 747-761.

Mino, Y., 1942. Basis Therories of Geomorphology. Kokon-Shoin, Tokyo, 517pp (in Japanese).

Montgometry, D.R., Dietrich, W.E., 1992. Channel initiation and the problem of landscape scale. Science 255, 826-830.

Oguchi, T., 1997. Drainage density and relative relief in humid steep mountains with frequent slope failure. Earth Surface processes and Landforms 22, 107-120.

Powers, P.S., Chiarle, M., Savage, W.Z., 1996. A digital photogrammetric method for measuring horizontal surficial movements on the Slumgullion Earthflow, Hinsdale County, Colorado. Computers & Geosciences 22, 651-663.

Pyle, C.J., Richards, K.S. Chandler, J.H., 1997. Digital photogrammetric monitoring of river bank erosion. Photogrammetric Record 15, 753-764.

Schumm, S.A., 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Geological Society of America Bulletin 67, 597-646.

Smith, K.G., 1958. Erosional processes and landforms in Badlands National Monument, south Dakota. Geological Society of America Bulletin 69, 975-1008.

Strahler, A.N., 1952. Dynamic basis of geomorphology. Bulletin of the Geological Society of American 63, 929-938.

Tailing, P., Sowter, M.J., 1999. Drainage density on progressively tilted surfaces with different gradients, Wheeler Ridge, California. Earth Surface Processes and Landforms 24, 809-824.

Tucker, G.E., Bras, R.L., 1998. Hillslope processes, drainage density, and landscape morphology. Water Resources Research 34, 2751-2764.

Tucker, G.E., Catani, F., Rinaldo, A., Bras, R.L., 2001. Statistical analysis of drainage density from digital terrain data. Geomorphology 36, 187-202.

Uto, K., Hayakawa, Y., Aramaki, S., Osaka, J., 1983. Geologic Map of Kusatsu-Shirane Volcano. Geological Survey of Japan.

Vogt, J., Colombo, R., Bertolo, F., 2003. Deriving drainage networks and catchment boundaries: a new methodology combining digital elevation data and environmental characteristics. Geomorphology (in press)

Westaway, R.M., Lane, S.N., Hicks, D.M., 2000. The development of an automated correction procedure for digital photogrammetry for the study of wide, shallow, gravel-bed rivers. Earth Surface Processes and Landforms 25, 209-226.

Yatsu, E., 1950. On relief energy of the Chichibu Mountains, Japan. Transactions Otsuka Geographical Association 6, 323-330 (in Japanese).