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Drainage density, slope angle, and relative basin position in Japanese bare lands from high-resolution DEMs

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Abstract

Relationships 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. Two of the bare lands were caused by volcanic eruptions 1 or 30–40 years ago, and the other one is a landslide scar formed more than 100 years ago. 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 subwatersheds were obtained from the DEMs and derived stream-nets. The relationship between drainage density and slope angle for each subwatershed 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, this correlation seldom occurs in the study areas. The two types of drainage density–slope angle relationships 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 subwatersheds within each study area seems to play a major role in determining the stages of channel development and, in turn, the types of drainage density–slope angle relationships.

Keywords: Stream-nets; Channel development; Digital photogrammetry; Geomorphometry; GIS

1. 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; Montgometry 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) summarized previous studies and noted that drainage density correlates positively with slope angle if overland flow is dominant, but negatively if shallow mass

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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 that 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. How the development of drainage systems with time affects the relationship between drainage density and slope angle is still uncertain. 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. Two of the bare lands were caused by volcanic eruptions 1 or 30–40 years ago, and the other one is a landslide scar which already existed 100 years ago. They include channels at various erosion stages because their eruption/landslide ages as well as local topographic relief are different.

2. The study areas

The study areas are located in the Usu volcano, the Kusatsu-Shirane volcano, and the Aka-Kuzure landslide in northern and central Japan (Fig. 1). Usu, a stratovolcano in SW Hokkaido, consists mainly of hypersthene dacite (Kadomura et al., 1988). The studied watershed has an area of 0.18 km^2 and altitudes of ca. 530 to 710 m (Fig. 1, U). The watershed underwent thick deposition of volcanic ash and pumice during eruptions between August 1977 and September 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 were widely extended by the summer of 1979 because of overland flow (Kadomura et al., 1983). All the rills and gullies cut into unconsolidated tephras with lithic fragments supplied by the 1977–1978 and older eruptions (Chinen and Kadomura, 1986). Only sparse grass vegetation existed in the study area until the early 1980s.

Kusatsu-Shirane is an active volcano in central Japan. Historical eruptions occurred in 1882, 1932, 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, KS). It has an area of 0.19 km^2, altitudes of ca. 1950 to 2100 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. The area mostly corresponds to the Shirane Pyroclastic Cone covered with thick unconsolidated volcanic ash, lappili, and blocks (Uto et al., 1983; Hayakawa and Yui, 1989). The Mizugama Lava Dome, composed of andesite, occupies a small part of the study area but no distinct gullies occur on it.

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 ca. 1190 to 1920 m (Fig. 1, AK). 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 100 years ago. The surface of the landslide is finely dissected and almost devoid of vegetation showing a badland-type landscape, despite the bedrock is consolidated. Field observations and the interpretation of large-scale air photos indicate that erosion is dominated by shallow and rapid mass-wasting on steep slopes, with subsequent removal by running water. The removed clastic sediment has formed a small alluvial fan immediately below the landslide (Chigira and Kiho, 1994).

3. Data

3.1. DEMs and orthophotos

Digital photogrammetry was applied to 1:8000 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

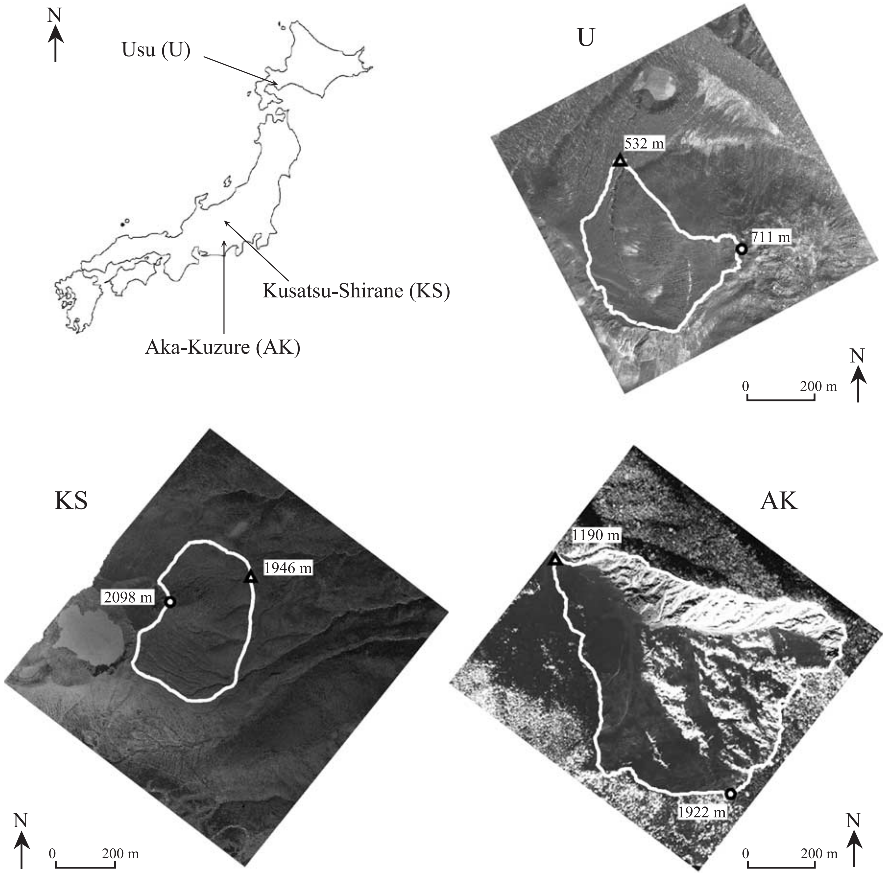

Fig. 1. Locations and orthophotos of three study areas. Circle: highest point; triangle: lowest point.

(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 1:8000 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 the 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 the Center for Spatial Information Science, the University of Tokyo. The 1-m DEM for Aka-Kuzure was also generated using the Leica-Helava DPW at Tamano Consultant, 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. The numbers of the models for Usu, Kusatsu-Shirane, and Aka-Kuzure are two, three, and one, respectively,

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

Area	Airphotos (1:8000) period	DEM errors (m)			
		Stereo pair	*X*	*Y*	*Z*
Usu	Oct 1979	1	0.1522	1.0026	0.0451
		2	1.2196	1.6909	0.3517
Kusatsu-Shirane	Aug 1985	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	1	1.9991	1.8387	0.7818

corresponding to the number of stereo-pairs used for each area. Then 1-m DEMs and orthophotos (Fig. 1) were generated using the obtained models.

The quality of the constructed DEMs looks sufficient for general topographic analysis. The root mean-square error (RMSE) at each ground control point (GCP) is 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.

3.2. 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 via a number of methods. (e.g., Mark, 1984; Martz and Garbrecht, 1992). The most common method, which is often implemented in 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 determine the point of channel initiation for Usu and Kusatsu-Shirane, we therefore 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 KS) 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 often attain ridges because of 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. We developed a macro program for ArcView for this stream ordering. Since this method identify all the cells as streams, we examined the density of major streams. Visual comparison between the orthophotos and the distribution of channels with different stream orders suggested that distinct gully-type channels generally correspond to the fourth- and higher order streams. Thus, such streams were regarded as the elements of stream-nets in Aka-Kuzure (Fig. 2A, AK).

3.3. Subwatersheds

To examine stream-net properties in relation to local topographic variations, subwatersheds within each study area were delineated using the DEMs. Both the area of each subwatershed and the total number of the subwatersheds should be adequately large for statistically meaningful analyses. Thus, we delineated 20 second-order subwatersheds in Usu (designated as U01 to U20), 14 second-order subwatersheds in Kusatsu-Shirane (KS01 to KS14), and 54 sixth-order subwatersheds in Aka-Kuzure (AK01 to AK54) (Fig. 2B). The area of the subwatersheds ranges from ca. 1200 to 11600 m^2 for Usu, 4900 to 11800 m^2 for Kusatsu-Shirane, and 2200 to 5600 m^2 for Aka-Kuzure. Each subwatershed was further divided into 10×10 m raster grid cells to examine the variation of morphometric characteristics within a subwatershed.

3.4. Morphometric parameters

The total length of channels in each subwatershed was computed using our own C++ algorithm to derive drainage density. One of four channel lengths, 0, 1, 1.21, or 1.41 m, was allocated to each grid cell. 0 m length was given to cells outside channels, and the other three lengths were given to channel cells (Fig. 3A) based on the bending and directions of channels (Fig. 3B). The calculated drainage density for each subwatershed ranges from 0.02 to 0.11 m/m^2 for Usu, 0.03 to

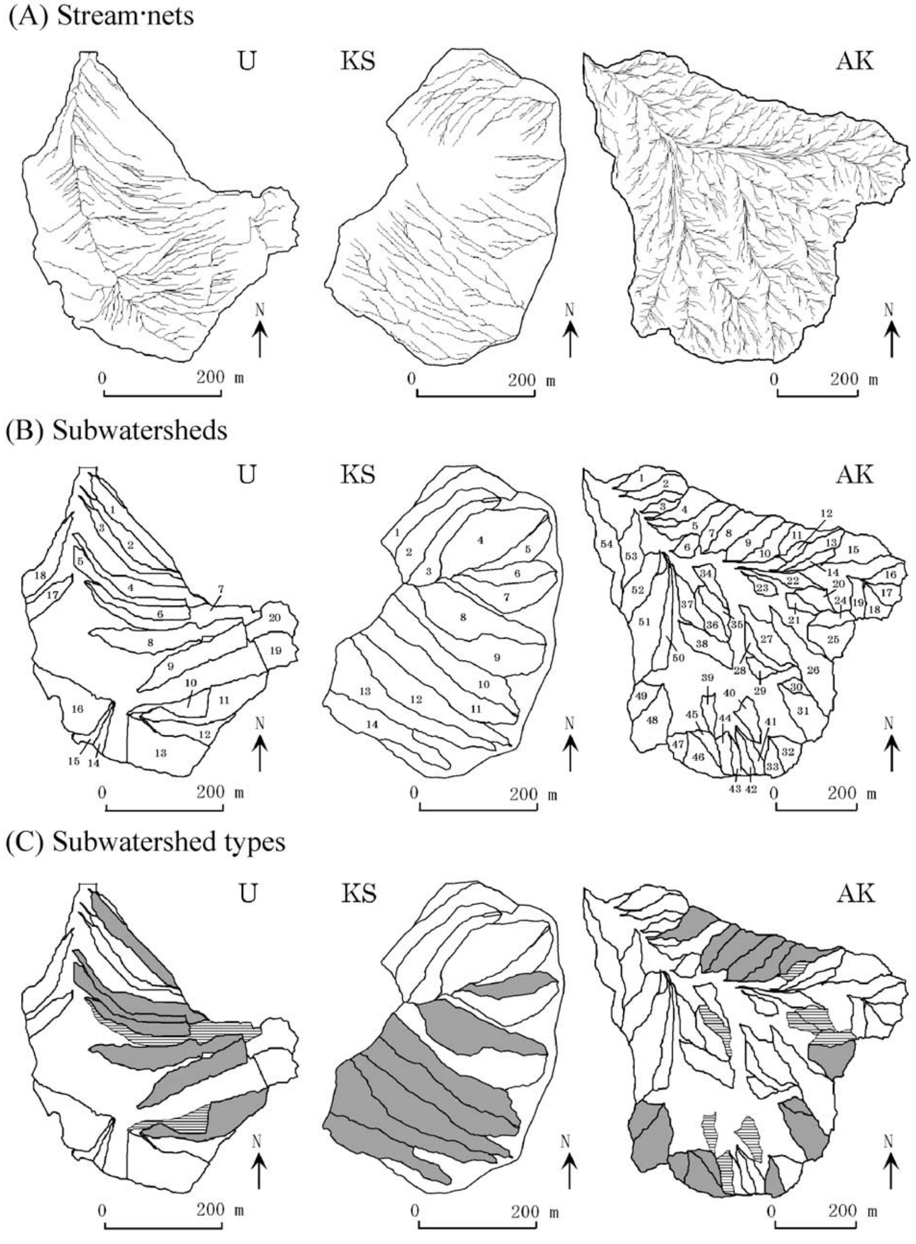

Fig. 2. (A) Stream-nets, (B) subwatersheds, and (C) subwatershed types in Usu (U), Kusatsu-Shirane (KS) and Aka-Kuzure (AK). White subwatersheds in (c): Type 1, gray subwatersheds: Type 2, hatched subwatersheds: nonclassified.

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 × 10 m cell within a subwatershed was also computed.

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 subwatershed and each 10 m × 10 m cell was computed. The mean slope angle for each subwatershed was 15° to 24° for Usu, 18° to 28° for Kusatsu-Shirane, and 43° to 57° for Aka-Kuzure.

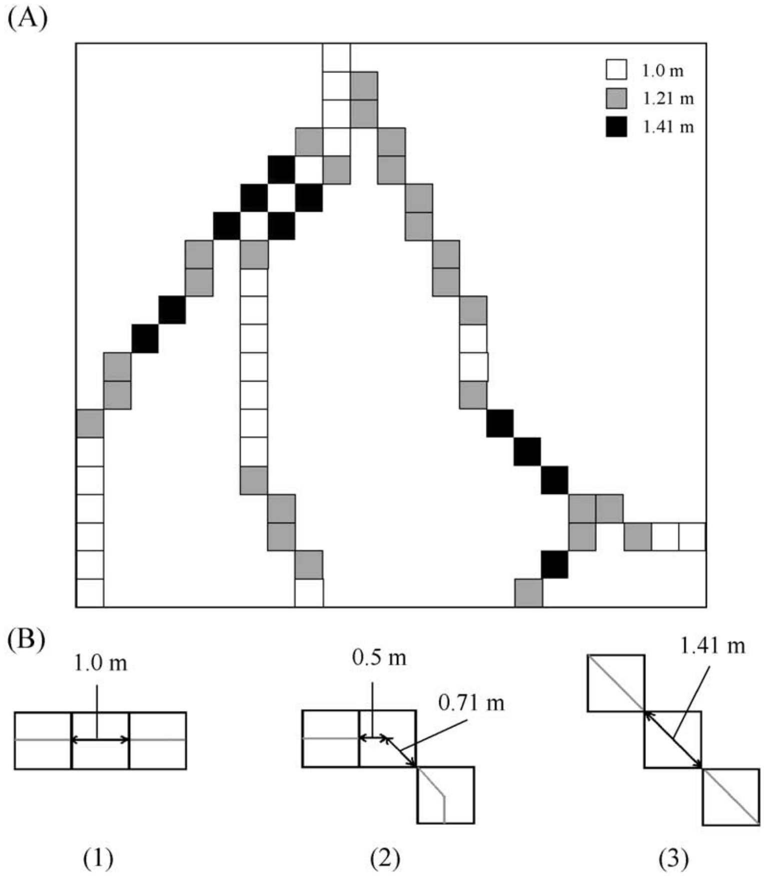

Fig. 3. (A) Stream lengths for grid cells. White squares: 1 m; gray squares: 1.21 m; black squares: 1.41 m; non-squared cells: 0 m. (B) Examples of cells with the three stream lengths.

Relative height (H_r) is defined to express the relative location of a 10 × 10 m cell within a subwatershed:

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

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

4. Data analysis

4.1. Slope angle and drainage density

The relationship between slope angle and drainage density was examined for each subwatershed. Using data for the 10 m × 10 m grid cells within a subwatershed, mean drainage density for each 2° slope bin was computed and plotted against slope angle. The bin size was operationally determined to assure relatively large numbers of both slope classes and data belonging to each bin. Then the quadratic equation was fitted to approximate the slope angle–drainage density relationship for each subwatershed. Fig. 4 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 relationships for the other 82 subwatersheds can also be classified into the two types

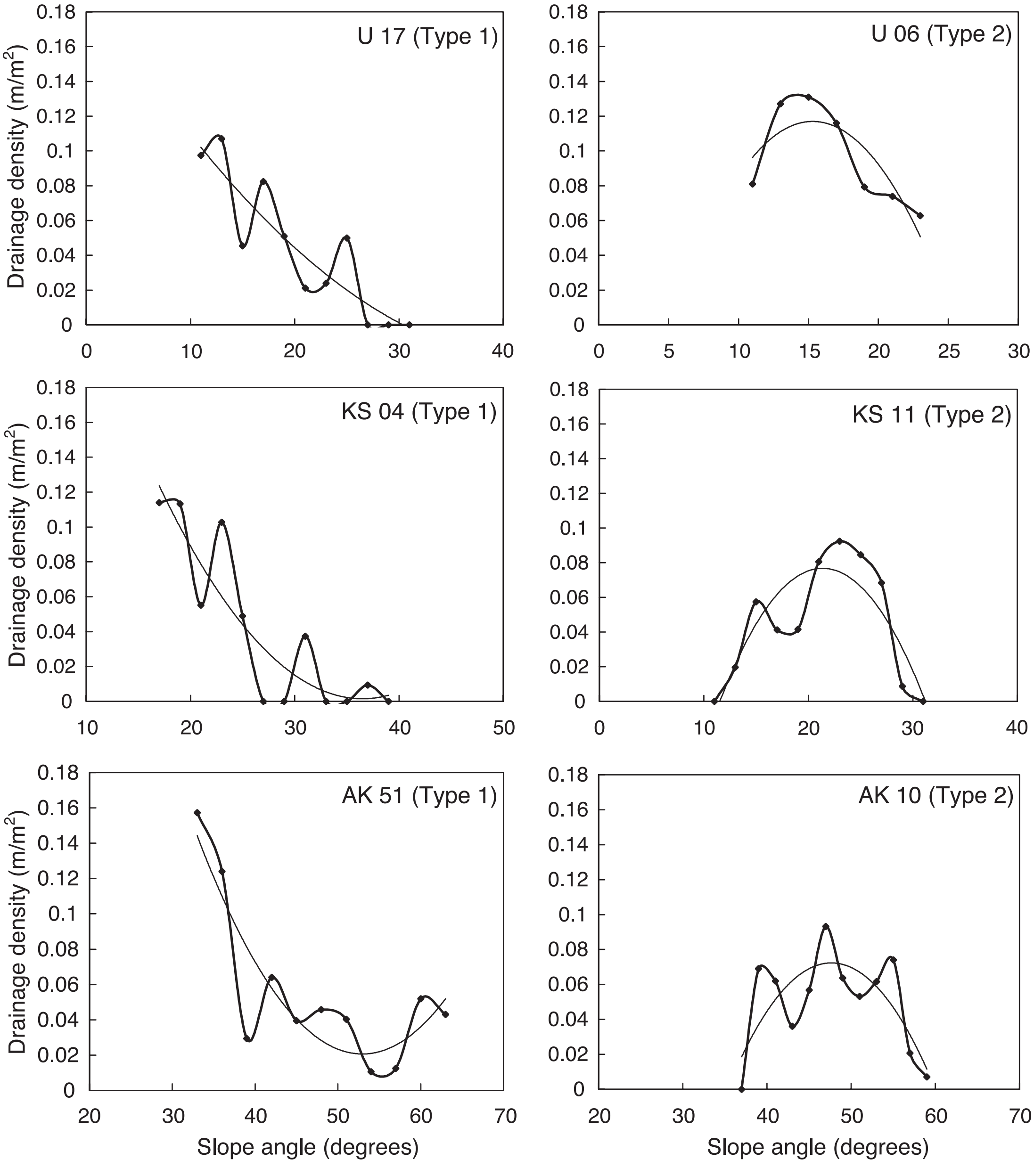

Fig. 4. Examples of two types of drainage density–slope angle relationships. Thin lines show approximation by quadratic equations. Type 1 is downward sloping (and concave). Type 2 is convex.

(Fig. 5) except two in Usu (U07 and 10) and eight in Aka-Kuzure (AK12, 20, 21, 24, 35, 39, 40, and 44) with various other relationships such as upward sloping, constant, and concave upward. The trend lines for Type 1 are mostly concave upward (Fig. 5). Fig. 2C shows the distribution of subwatersheds with the different types.

Fig. 6 is a plot of mean slope angle and mean drainage density for each subwatershed classified according to Types 1 and 2. The two types in Usu

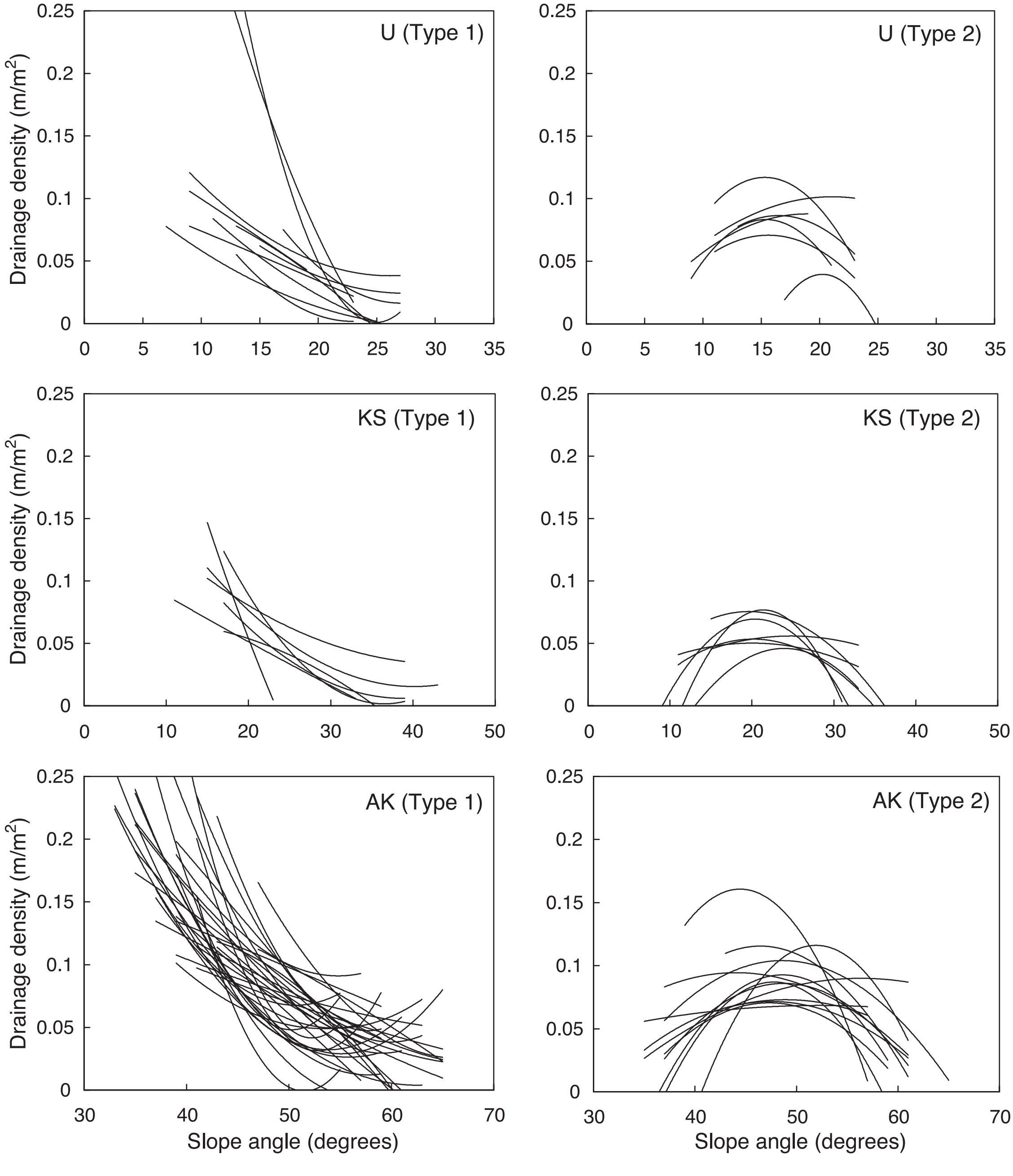

Fig. 5. Trend lines of two types of drainage density–slope angle relationships. U: Usu; KS: Kusatsu-Shirane; AK: Aka-Kuzure.

are clearly separated since Type 1 has lower drainage density than Type 2. Conversely, some Type 1 subwatersheds in Aka-Kuzure tend to have higher drainage density than Type 2, since most subwatersheds 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.

The negative and convex correlations between slope angle and drainage density are generally indistinct in Fig. 6, reflecting the fact that the

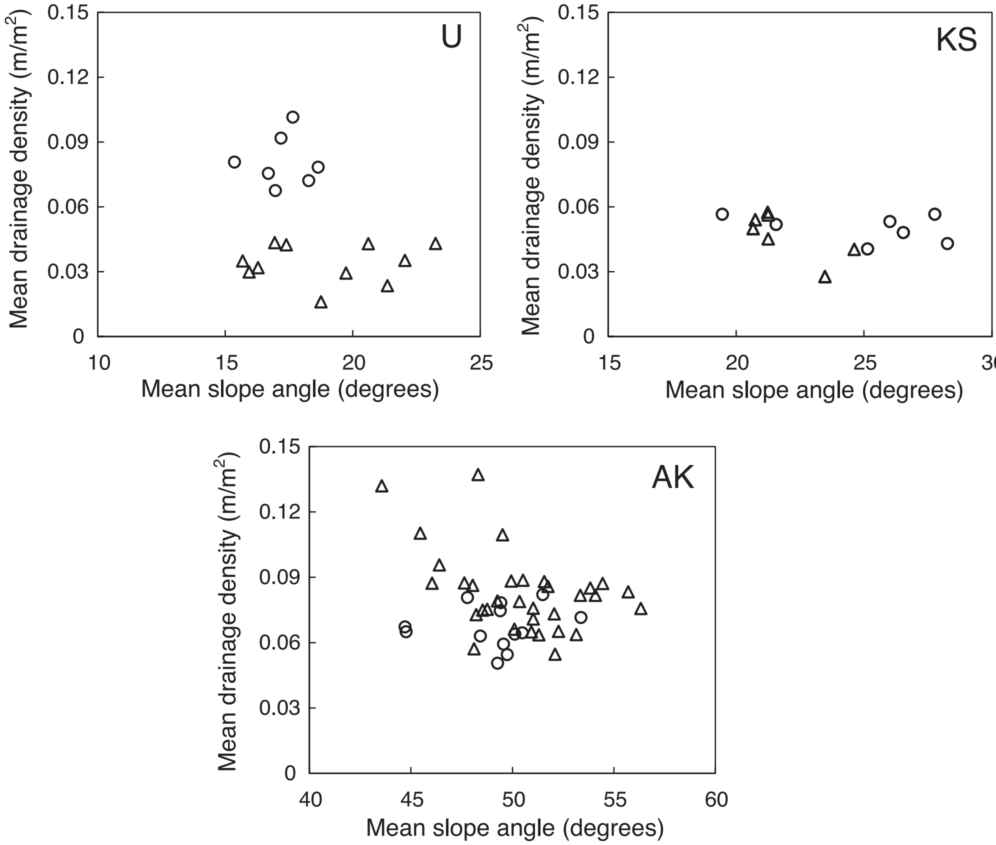

Fig. 6. Plot of mean drainage density and mean slope angle for each subwatershed. U: Usu; KS: Kusatsu-Shirane; AK: Aka-Kuzure. Triangles: Type 1 (download sloping); Circles: Type 2 (convex).

plotted mean values for each subwatershed were computed from a large number of highly variable data. In other words, the Types 1 and 2 can be identified from the detailed high-resolution data but not from the generalized data. However, even the mean drainage density for Type 1 subwatersheds tends to correlate negatively with mean slope angle in Kusatsu-Shirane and Aka-Kuzure (Fig. 6, KS and AK), which is consistent with the inference from the detailed data.

4.2. Distribution of subwatershed types

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

4.3. 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

Table 2
Parameters of stream-net structure for three study areas

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	

Note the method of stream ordering for Aka-Kuzure differs from that for Usu and Kusatsu-Shirane.

than Type 1. In Aka-Kuzure, by contrast, Type 2 has smaller bifurcation ratios and stream-length ratios than Type 1.

4.4. Relative height and drainage density

The relationship between relative height and drainage density for each subwatershed was also examined. Relative height was operationally divided into 10 bins with a 0.1 interval. Using the 10 m × 10 m grid cell data within a subwatershed, mean drainage density for each bin was computed and plotted against slope angle; and the quadratic equation was fitted to their relationships. Fig. 7 shows six examples of the plots, and Fig. 8 shows the approximated trend lines for all the Type 1 and Type 2 subwatersheds. Types 1 and 2 in Usu and Kusatsu-Shirane also differ in the relationship 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 are convex upward (Fig. 8). In other words, drainage density–slope angle relationships and drainage density–relative height relationships tend to have similar trends. This correspondence may reflect a commonly observed topographic characteristic of a watershed: steep slopes tend to occur in upper parts where low-order streams are frequent (e.g., Schumm, 1956). The correspondence also generally holds true for Aka-Kuzure, although the concavity of Type 2 is less marked and more exceptions can be found (Fig. 8).

5. Discussion

5.1. 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. 6, U; Table 2) show stream-nets in the Type 1 subwatersheds are more immature than those in the Type 2 subwatersheds. The biggest difference often occurs in the middle height of each subwatershed: mean drainage density at a relative height of 0.5 is around 0.05 for Type 1, but around 0.11 for Type 2 (Fig. 8, U). Drainage density of Type 1 for medium slope angles (15° to 20°) also tends to be lower than that of Type 2 (Fig. 5, U). These observations support the inference that Type 1 in Usu corresponds to earlier channelization stages because channel extension usually starts at the lower flat areas and subsequently proceeds to higher steeper areas. The change in drainage density–slope angle relationships from Type 1 to Type 2 can be accounted for by the enhanced channelization in the middle to upper subwatershed as erosion progresses. Drainage density for the lower part of the Type 1 subwatersheds 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 the location and general inclination of subwatersheds. The Type 2 subwatersheds in Usu have large mean inclination (Fig. 6, U) and tend to occur in the central area close to the master gully (Fig. 2C, U), and thus have reached more advanced channelization stages than the Type 1 subwatersheds in the periphery. In contrast, the effects of geology on the subwatershed types seem to be limited, because all the streams in the Usu area cut into similar unconsolidated material.

5.2. Kusatsu-Shirane area

The Type 1 and Type 2 subwatersheds in Kusatsu-Shirane have topographic differences similar to those

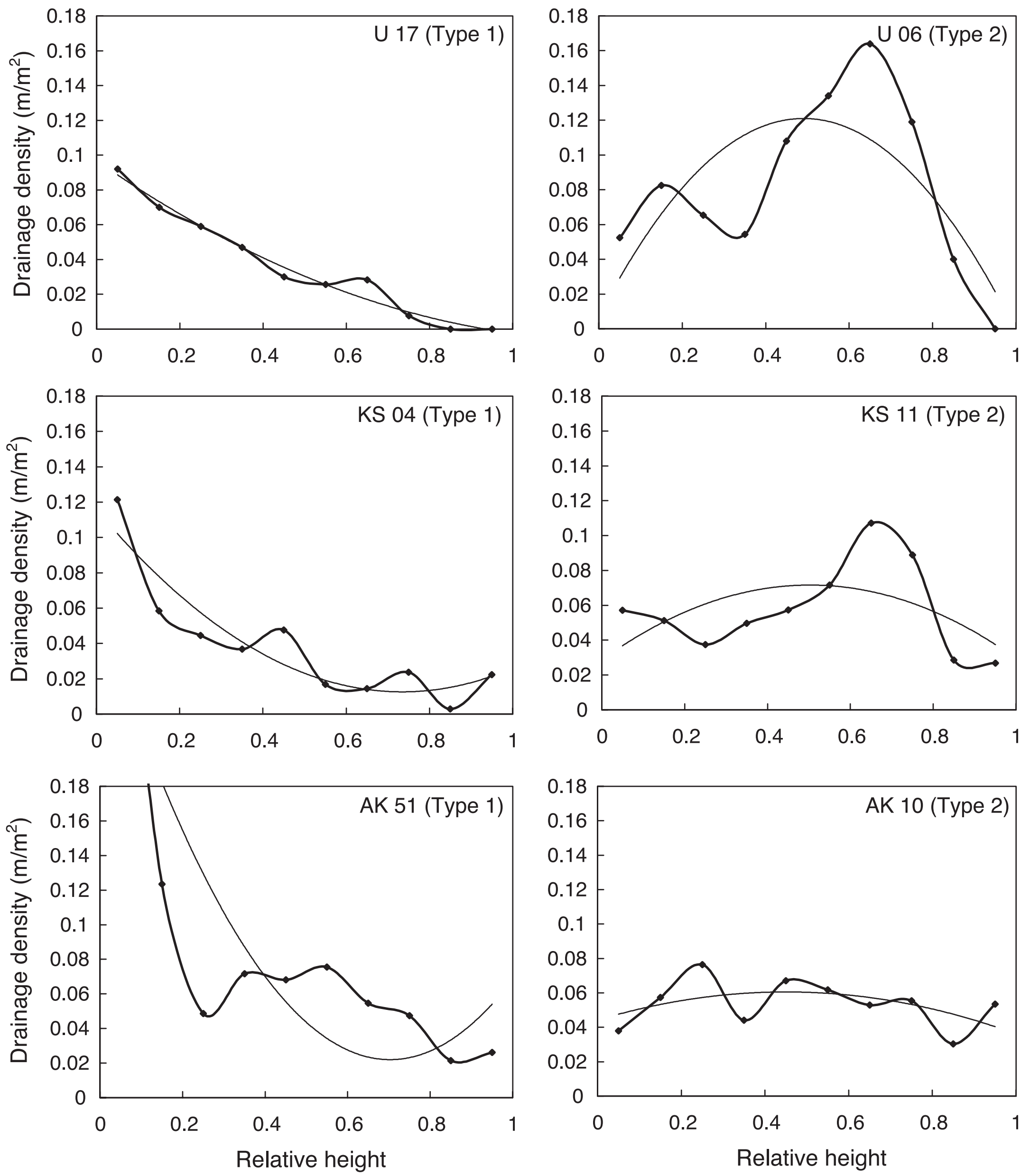

Fig. 7. Examples of drainage density–relative height relationships. Thin lines show approximation by quadratic equations. Type 1 and Type 2 are determined based on drainage density–slope angle relationships (see Figs. 4 and 5).

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 subwatershed (Fig. 8, KS; Table 2), suggesting that Type 2 is at more advanced channelization stages. Unlike Usu, mean drainage density does not differ according to the types (Fig. 6, KS). Although the drainage density for the middle relative height of Type 1 is lower than that of Type 2, the density for the lowest part of Type 1 (relative height = 0.05) is higher than that of Type 2

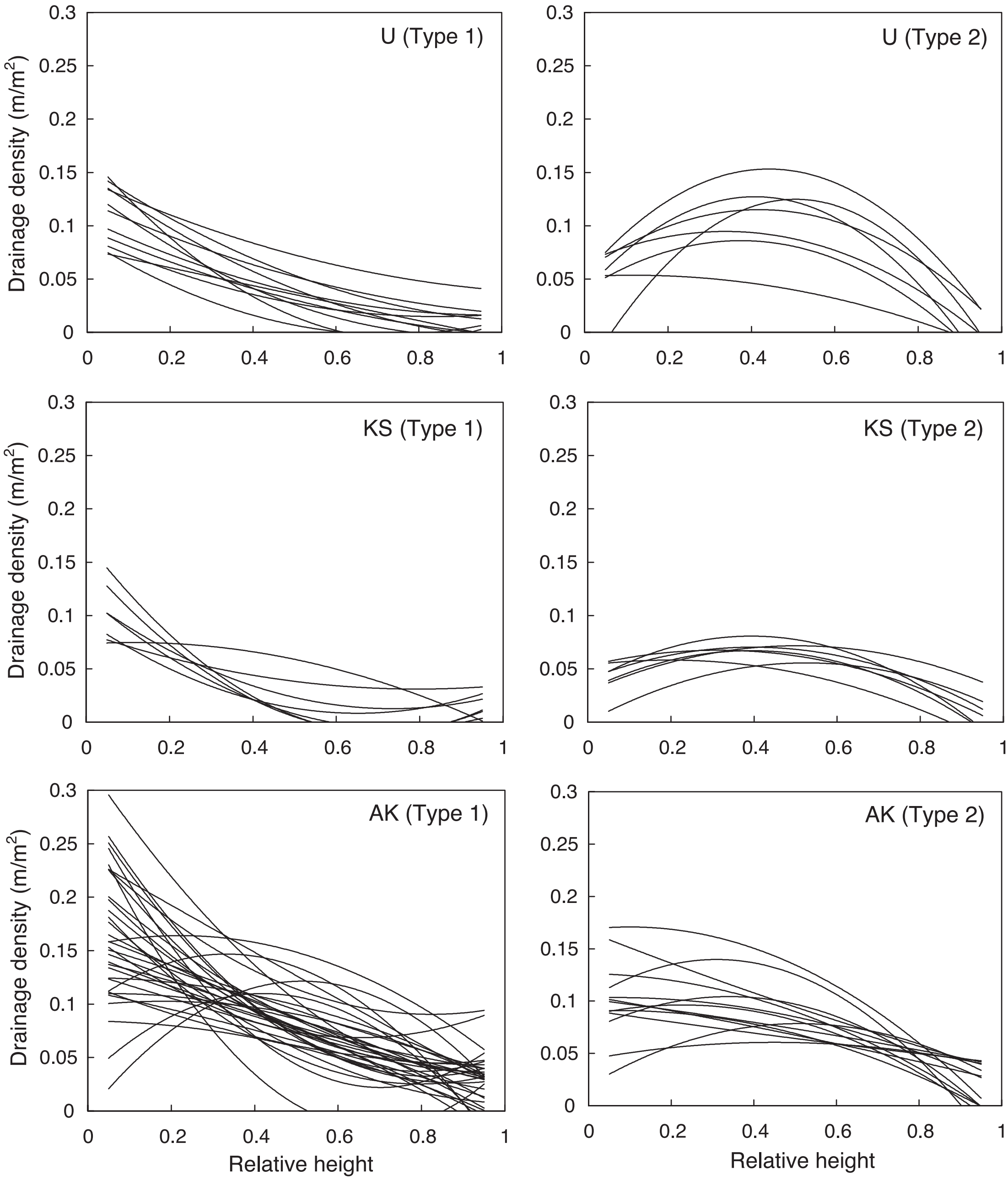

Fig. 8. Trend lines showing drainage density–relative height relationships, classified according to types of drainage density–slope angle relations. U: Usu; KS: Kusatsu-Shirane; AK: Aka-Kuzure.

(Fig. 8, KS), resulting in the similar mean drainage density for the two types. Drainage density for low slope angles (< 20°) of Type 1 is apparently higher than that of Type 2 (Fig. 5, KS). Therefore, marked stream integration seems to have occurred at the lower and flatter areas of the Type 2 subwatersheds. Moreover, the Type 2 subwatersheds are located in the southern area where incision by master gullies is more

evident than in 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. Like Usu, all the streams cut into similar unconsolidated rocks, indicating that the two types of drainage density–slope angle relationships for Kusatsu-Shirane are ascribable to different stages of stream-net growth rather than geology.

5.3. 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 relationships for Types 1 and 2 in Aka-Kuzure differ in the same manner as those in the other two areas (Fig. 8, AK), Type 1 has larger bifurcation ratios and stream length ratios than Type 2, which is the 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. 6, AK), 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 subwatersheds (Fig. 8, AK), which can be related to base-level lowering at the bottom of the landslide. The topography of a small entrenched alluvial fan immediately below the Aka-Kuzure landslide indicates that the stream flowing from the landslide has 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. Such processes can be assumed to have been more enhanced in the Type 1 subwatersheds than Type 2, especially in the lower and flatter parts of the subwatersheds adjacent to the major streams. This assumption conforms to the peripheral distribution of the Type 2 subwatersheds and their smaller mean slope angles (Figs. 2 and 6, AK) because hillslope incision in response to base-level lowering should be limited in gentle terrains apart from the master stream.

Geology seems to play only a limited role in determining the subwatershed types in Akakazure, despite the area is underlain by three different rocks: sandstone, shale, and their alternation. The subwatersheds were grouped into three according to the dominant rock type. The percentage of Type 1 in each group ranges from 43 to 71, while that of Type 2 is 25 to 43, and that of the nonclassified type is 0 to 17. In other words, no clear correlations are observed between the rock types and the subwatershed types.

5.4. Factors affecting drainage density–slope angle relationships

The detailed analysis of stream-net structure and watershed geomorphometry for the three areas has provided fresh insights into drainage density–slope angle relationships. 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 nonlinear relationships 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 subwatersheds. In Usu and Kusatsu-Shirane, drainage density–slope angle relationships shift from Type 1 to Type 2 with the progress of channelization stages owing to channel extension in the middle parts of subwatersheds and channel integration in the lower parts. In Aka-Kuzure, however, formation of new channels in response to base-level lowering has led to a shift from Type 2 to Type 1. In summary, the advance of channelization stages can lead to bidirectional changes between the two types of drainage density–slope angle relationships.

About 11% of the subwatersheds studied have drainage density–slope angle relationships other than the Types 1 and 2. The characteristics of the exceptional relationships are highly variable, and the locations of such subwatersheds do not clearly correspond to relative basin positions (Fig. 2C), although their occurrence may be infrequent in lower areas. Future research is necessary to explain the occurrence of the exceptional relationships.

6. 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 subwatersheds.

Although previous studies suggested that the relationship 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 relationships 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 relationships 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, 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 the future for a better understanding of topographic effects on channel distribution.

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