Analyses of watershed longitudinal/transverse profiles and stream-net structure using high-resolution DEMs

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Abstract—**We applied DEMs at 1-m resolution (for small bare lands) and at 10-m resolution (for broad forested areas) in Japanese hills and mountains for quantitative analyses of longitudinal/transverse profiles of watersheds and stream-net structure, with special attention to watershed evolution and regional relief. Many statistical morphometric parameters have distinct and consistent correlations with relief in both the 1-m and 10-m DEM areas, and most topographic characteristics of watersheds in the high-relief areas are simpler and more organized than those in the low- to middle-relief areas. The results of this research indicates that high-relief terrains have more mature conditions close to equilibrium, although some other morphometric parameters also indicate the effects of marked differences in bedrock strength. In addition, very detailed stream-net structure represented by 1-m DEMs significantly reflect local factors such as proximity to the trunk stream, especially if channels are at the early stages of erosion, while those represented by 10-m DEMs correspond more simply to regional relief.**

I. INTRODUCTION

Watersheds and stream-nets have been regarded as fundamental units in geomorphology and hydrology [1, 2]. Significant attention has been paid to their morphological characteristics and evolution processes [e.g., 3, 4, 5, 6, 7, 8, 9]. Numerous studies have dealt with river longitudinal profiles and stream-nets [e.g., 10, 11, 12, 13, 14]. However, only a small number of studies have analyzed the characteristics of the transverse profiles of watersheds, although the shape of transverse profiles is important for understanding dominant erosional processes [e.g., 11, 15, 16]. Moreover, almost no studies have examined both the longitudinal and transverse characteristics of watersheds at the same time, although they seem to be fundamental to describe watershed topography. The scarcity of transverse-profile studies may be explained from difficulties in data sampling in the field as well as from DEMs (Digital Elevation Models) using existing software packages. Detailed studies on stream-nets in watersheds at various stages of their evolution have also been rare, since the usual resolution of DEMs is insufficient to investigate shallow and narrow channels at early erosional stages. This study applied high-resolution DEMs, GIS and computer programming techniques to the analyses of longitudinal and transverse profiles and stream-net structure in Japanese watersheds. Based on the results, the evolution processes of watershed form and stream-net structure are inferred. Special attention is paid to topographic differences between low-relief areas at early stages of stream-net development and high-relief areas with mature stream-nets.

II. STUDY AREAS

The study areas include bare lands on volcanoes (Usu and Kusatsu-Shirane) and in a large landslide (Aka-Kuzure) to enable the construction of DEMs with a 1-m resolution using digital aerial photogrammetry without disturbance by vegetation cover, and detailed analyses of stream-nets at both early and late erosional stages. Three typical Japanese hills and mountains, the Tama, Hamada and Shiojiri regions, were also selected as study areas, to look into the characteristics of more usual types of watersheds using DEMs with a 10-m resolution produced from contour data.

III. METHODS

The DEMs allowed the detailed analyses of watershed morphology. First, subwatersheds in each study area were delineated using the DEMs; then longitudinal and transverse profiles of each subwatershed were extracted.

To acquire transverse profiles with small distortion, the spline function was fitted to grid cells showing the trunk stream to smooth the stream-line direction, and data of transverse profiles were extracted at a certain interval along the trunk stream (Fig. 1). Then, some morphometric parameters representing a shape of the transverse profile, such as width, relief, standard deviation of height, and skewness of slope, were acquired. A quadratic equation was fitted to the relationship between the shape parameters and the flow distance measured along the master stream to quantify the tendency of changes in parameter values. The quadratic equations fitted well to some subwatersheds. For the other subwatersheds with more complicated topographic changes, split points were extracted to divide a subwatershed into a few downstream and upstream sections, so that the relationships for each section can be examined. Similarly, the anomalous point, which indicates marked deviation of river-bed height from the general trend of a river profile, was identified for each watershed. The methods of identifying these points are described in our previous paper [17]. Relationships among longitudinal, transverse and overall watershed characteristics were also investigated using parameters such as the exponent of power functions of longitudinal profiles, overall watershed gradient and the hypsometric integral derived from the DEMs.

Stream-nets in each subwatershed were also delineated using the DEMs and orthophotos, and data of drainage density, stream orders, the bifurcation ratio, and the stream-length ratio were derived. Moreover, local slope angle and relative height at a small area of a watershed were calculated from the DEMs.

IV. RESULTS AND DISCUSSION

The identified split and anomalous points in a watershed tend to occur at the same location (Fig. 2), indicating that the longitudinal and transverse characteristics of watersheds are systematically related. Analyses of the longitudinal and transverse profiles have shown that the topography of watersheds in the high-relief regions is more organized than that in low- to middle- relief regions. For example, Table 1 shows the frequency of the split and anomalous points for all the study areas. In the low- relief areas, the number of subwatersheds with the split points is similar to that without split points. In the middle-relief areas, the number of subwatersheds with split points is about twice as many as that without the split points. In the high-relief areas, the number of subwatersheds without split points is about twice as many as that with the split points. Similarly, the frequency of anomalous points in the middle-relief areas is high, while that in the high-relief areas is low, and that in the low-relief areas is intermediate. This result conforms to the previous models of landform evolution in that higher large-relief terrains in tectonically active regions tend to approach equilibrium. The characteristics of some morphometric parameters, however, also indicate that the watersheds in the middle-relief regions are less organized than those in the low-relief regions. This observation may be explained from differences in bedrock. Fined-grained volcanic ash or non-consolidated bedrock in the hilly lands may have led to more flexible change in topography, leading to relatively organized watershed shapes than in the middle-relief areas.

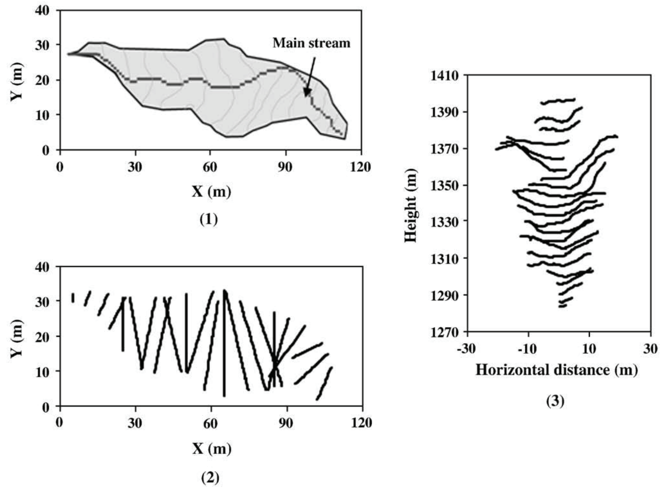

Figure 1. Delineation of watershed transverse profiles. 1) Subwatershed. 2) Location of profiles. 3) Extracted transverse profiles.

Although the distribution of the split/anomalous points suggested a correlation between the longitudinal and transverse characteristics, relationships among the average watershed slope, the longitudinal slope and the transverse slope indicate that the two characteristics play different roles in determining the entire watershed topography. The average watershed slope in the high-relief regions mainly reflects the longitudinal slope, while the effects of the transverse slope become stronger in the lower-relief regions. Correlations among the other longitudinal, transverse and overall watershed characteristics tend to be weak or insignificant in the high-relief regions, meaning that the topographic characteristics of watersheds in the high-relief regions are relatively simple and represented by the longitudinal gradient alone. The shape of longitudinal profiles in the high-relief regions are also simple in terms of curvature, because the exponents of power functions fitted to the longitudinal profiles are close to unity. Such detailed characteristics of topography in the equilibrium state have rarely been discussed in the previous studies.

The detailed analysis of stream-net structure and watershed geomorphometry has provided fresh insights into drainage density–slope angle relationships. Although previous studies suggested that slope angle and drainage density correlate positively if overland flow promotes erosion, and correlate negatively if shallow mass-wasting is dominant [6, 7, 18], the results

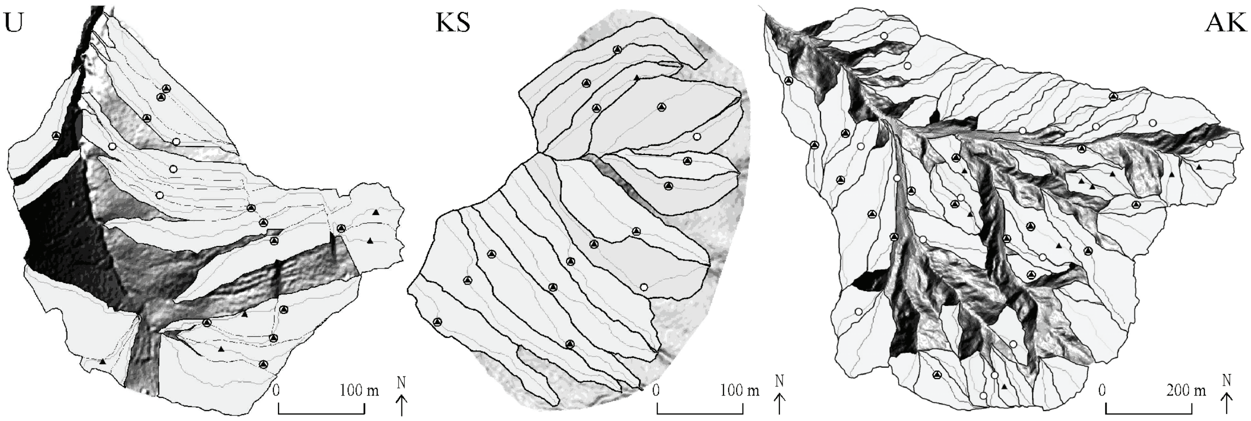

Figure 2. Locations of split points and anomalous points in areas with 1-m DEMs. Circle: split point; triangle: anomalous point. U: Usu, KS: Kusatsu-Shirane, AK: Aka-Kuzure.

of this study do not support this inference, and revealed the common occurrence of nonlinear relationships (e.g., Fig. 3). In addition, positive correlations between drainage density and slope angle often occur in high-relief mountains subjected to frequent mass-wasting, which also differs from the observations of some previous studies.

In the 1-m DEM areas, differences in drainage density–slope angle relationships most likely reflect differing stages of channel development, which often correspond to the location of subwatersheds. The drainage density–slope angle relationships tend to change with the progress of channelization stages owing to channel extension in the middle parts of subwatersheds and channel integration in the lower parts, as well as the formation of new channels in response to base-level lowering. In the 10-m DEM areas, drainage density–slope angle relationships more simply corresponds to regional relief. The difference between the 1-m DEM areas and the 10-m DEM areas seems to reflect the higher sensitivity of the stream-nets in the 1-m DEM areas to variation in local conditions.

In this study, the results of the profile and stream-net analyses were summarized in terms of the relationship between topographic characteristics and regional relief. Some other morphometric parameters also indicate the effects of marked differences in bedrock strength between the low-relief regions and middle-relief regions. The inferred effects of geology on the complexity of watershed structure should be confirmed based on additional case studies.

Table 1. Frequency of subwatersheds with or without split/anomalous points in the all study areas. U: Usu, KS: Kusatsu-Shirane, AK: Aka-Kuzure, T1 and Ta: low-relief areas in Tama region, Tb: middle-relief area in Tama region, H1 and H2: middle-relief areas in Hamada region, Sa: middle-relief area in Shiojiri region, S1 and Sb: high-relief areas in Shiojiri region.

Area	U	KS	AK	T1	Ta	Tb	H1	H2	Sa	S1	Sb
Without split points	10	0	33	23	14	14	18	14	11	14	20
With split points	10	14	17	23	17	28	51	30	19	7	12
(only one point/more)	(8/2)	(12/2)	(13/4)	(21/2)	(12/5)	(23/5)	(38/13)	(22/8)	(10/9)	(6/1)	(12/0)
Without anomalous points	7	1	30	30	21	22	39	23	14	20	29
With anomalous points	13	13	24	14	11	20	40	21	13	1	2
(only one point/more)	(9/4)	(11/2)	(19/5)	(13/1)	(9/2)	(18/2)	(27/13)	(19/2)	(5/8)	(1/0)	(1/1)

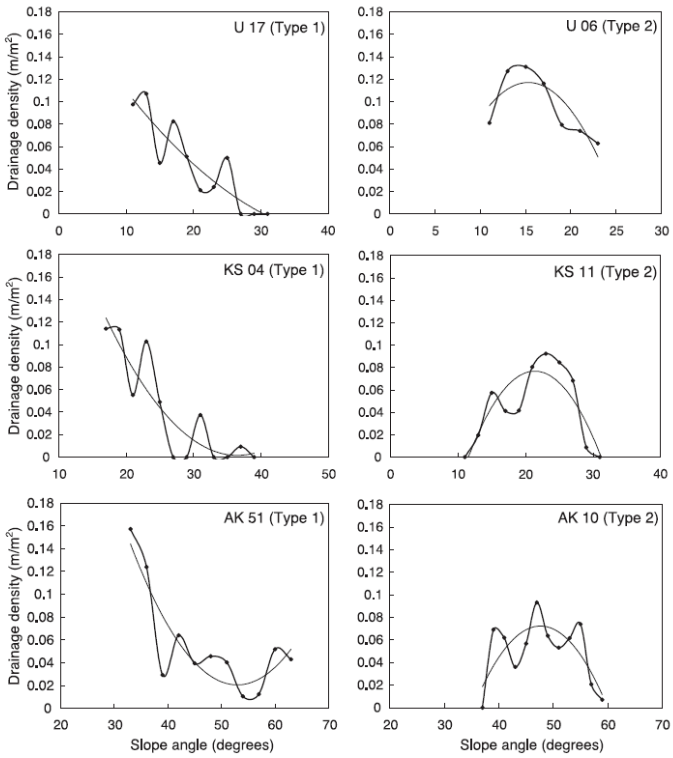

Figure 3. Examples of two types of drainage density–slope angle relationships for the subwatersheds in Usu (U), Kusatsu-Shirane (KS), and Aka-Kuzure (AK). Thin lines show approximation by quadratic equations. Type 1 is downward sloping (and concave), and Type 2 is convex.

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