Scale dependency of stream gradient calculation and its use to quantify bedrock river morphology

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Abstract—**Quantification of riverbed morphology in relation to landform development is an important issue in geomorphology. Here we examine not only stream gradient but also its changes with measuring scales in order to quantify bedrock river morphology and to extract knickzones, i.e., relatively steep reaches. The method uses a simple slope calculation at every point along stream lines having a regular horizontal spacing, with a variable measurement stick as a horizontal scale, to show the local steepness of rivers relative to adjacent reaches. Fluctuations in the local relative steepness indicate step-pool or riffle-pool-like morphology of bedrock rivers, which occur in differing spatial scales. Portions with high local relative steepness can be regarded as knickzones, which are numerously found across the Japanese mountain bedrock rivers from a 50-m resolution DEM. If such a relatively coarse DEM is used, large-scale fluctuations with hundreds of meters in horizontal scale are found, and the large knickzones can be related to hydraulic factors such as variations in flow velocity and/or flow perturbation around major stream confluences. When a finer DEM such as airborne LiDAR data at 1-m resolution is used, much smaller (on the order of 10-m horizontal scale) fluctuations in bedrock river morphology are found and they correspond to small knickpoints, waterfalls or step-pools found in the field.**

Keywords: Bedrock rivers, Stream gradient, Local relative steepness, Knickzones

INTRODUCTION

Morphology of bedrock rivers is a key to understand the development of landforms, because erosion in bedrock rivers sets the lower limit of mountain hillslopes [1, 2]. Longitudinal profiles of river sometimes follows the law that the stream gradient decreases proportionally to the downslope distance [3, 4], however, many bedrock rivers have unsmooth profiles with variations in their gradient. Knickzones, defined as locally steep reaches, is one of those anomalies in bedrock river longitudinal profiles, although quantitative investigations of their locations and forms have been limited.

Here we introduce a way to analyze the changes in stream gradient of bedrock rivers with various scale ranges, and to morphologically extract knickzones from digital elevation models (DEMs) using the scale-dependent changes in stream gradient. The scale dependency of stream gradient is important since calculation of slope gradient requires an appropriate scale range relevant to the nature of landforms [5, 6].

METHOD

Stream gradient calculation and local steepness

Longitudinal profiles of the rivers are extracted along the streams at a regular horizontal spacing [7, 8]. Stream gradient, G_d (m m^{-1}), is then measured at each sampling point with a variable measurement length of d (m). G_d is defined as:

$$G_d = \frac{E_1 - E_2}{d} \tag{1}$$

where E_1 and E_2 are elevation at 0.5d upstream and downstream from the sampling point, respectively. The local steepness, R_d (m^{-1}), is then defined as the ratio of scale-dependent decrease in the local variation in G_d at the same point, where G_d decreases as the length of measure stick (d) increases if the point is locally steep relative to the adjacent reaches. The changes in G_d along with an increasing d can be approximated based on linear regression:

$$G_d = \mathrm{a}d + \mathrm{b} \tag{2}$$

where a and b are constants. The local relative steepness R_d is then given as:

$$R_d = -\mathrm{a} \tag{3}$$

R_d can be used to characterize local morphometric features of riverbed. Also, a knickzone, or a locally steep reach, can be identified as the clusters of points having anomalously large R_d values.

Data preparation

For the regional-scale analysis, a 50-m DEM, which covers the whole Japanese Archipelago, was used as the source of stream gradient calculation. The DEM was derived from 1:25,000 topographic map of Japan. Major stream networks having a 0.1 km^2 source area at each channel head were extracted from the DEMs using hydrological processing modules in ESRI ArcGIS [9]. Using a 1:1,000,000 geologic map of Japan and dam location data, reaches on unconsolidated Quaternary deposits and reservoirs with artificial dams were excluded from the stream network. The total length of remaining reaches is 65,468 km. This covers most of major mountainous watersheds in the whole study area.

For the local scale analysis, an airborne Lidar (Light detection and ranging) DEM at a resolution of 1 m was used. The study area is the catchment of the Higashi-gouchi River (17.6 km^2), a tributary of the Ohi River, located in the south of the Southern Japanese Alps (Akaishi Mountains) in central Japan. The catchment has been managed by the University of Tsukuba as the Ikawa University Forest. Lithologic substrate in the area is the Shimanto Cretaceous strata comprised of deformed sandstones and shales. Stream networks in the area was extracted from the 1-m DEM.

Results and Discussion

Regional analysis

Based on the 50-m DEM, G_d with shorter length of d (320–1,760 m) shows local variations in stream gradient, and this range was used for calculating R_d. On the other hand, G_d with d of 3,040 m is referred to as the trend gradient, representing a large-scale stream gradient averaging local fluctuations.

Spatial distribution of R_d is summarized for 5-km neighborhood areas to compute the standard deviation of R_d (Fig. 1A). This represents how the riverbed is rough in terms of the gradient variation, and may indicate the localities of active erosion.

For the detection of knickzones, a threshold value for R_d of 1.42×10^{-5} m^{-1} is used, resulting in the identification of 5,753 knickzones along these major streams[7,8]. The frequency of knickzone occurrence is 0.088 km^{-1}, or one knickzone at every 11 km throughout the study area, occupying 3.21% of the total reach length. The average form of the knickzones is 44.7 m in height, 286 m in length, 0.147 m m^{-1} in gradient and 2.96×10^{-5} m^{-1} in R_d. These knickzones are abundant in upstream steep areas where hydraulic erosion is active, and a knickzone frequency tends to be constant around 0.5 km^{-1} for rivers steeper than 0.15 m m^{-1}.[8] The spatial distribution of knickzones summarized for 10-km neighborhood areas show high knickzone clusters in high elevation areas with volcanoes and steep uplifted terrains (Fig. 1B). This is basically unrelated to geologic differences in the mountains.

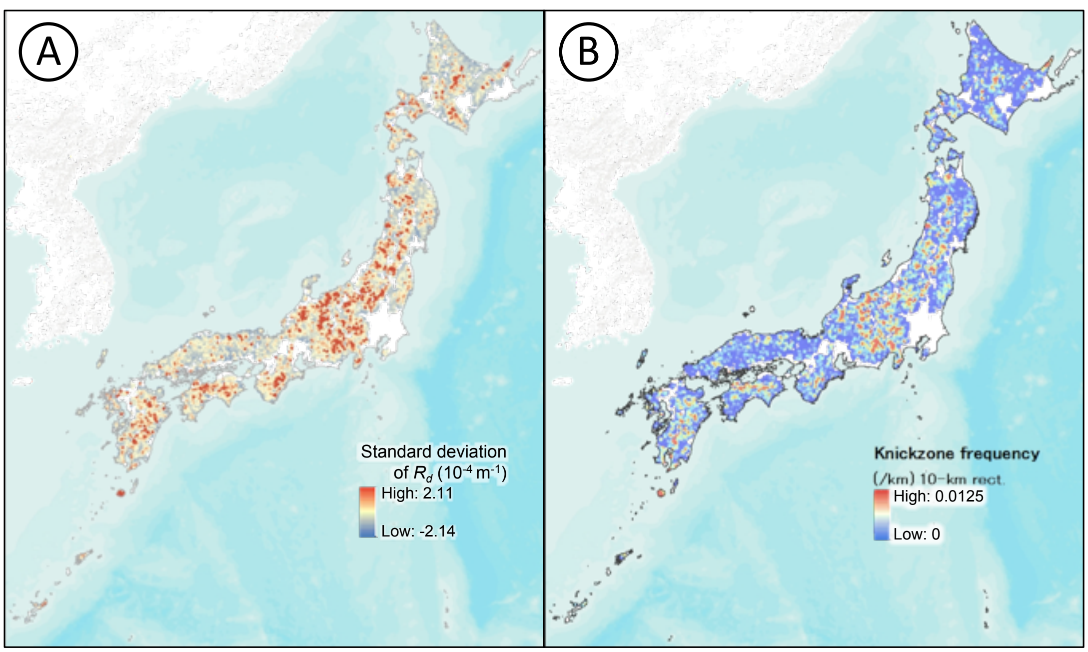

Figure 1. Spatial distributions of (A) standard deviation of the local relative steepness, R_d, and (B) knickzone frequency for the whole of Japan.

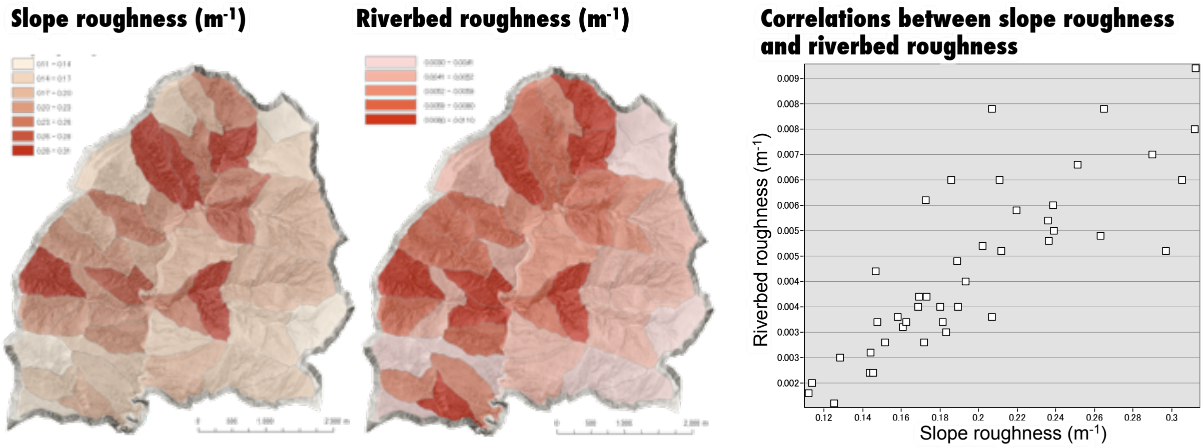

Figure 2. Spatial distribution and spatial relationship between slope roughness, defined as mean local curvature in 10-m neighborhood areas, and riverbed roughness, defined as the standard deviation of R_d for d = 3 – 30 m, summarized for subcatchments in the Ikawa study area.

Local analysis

Based on the 1-m DEM, G_d with lengths of d = 3–30 was used to compute R_d to quantify the local topographic features of bedrock rivers at a smaller length scale. Fourier analysis on the longitudinal changes in this R_d indicates the recurrence of local relative steepness at 20–30 m intervals, which may reflect stepped morphology of the riverbed with small knickpoints. Such knickpoints (waterfalls) are recognized in the field, reflecting lithologic features including joints and step-pool-like hydraulic features. A spatial correlation is found between the slope roughness based on curvature and riverbed roughness based on R_d for the subwatersheds (Fig. 2). This indicates linkage between stream-erosion processes and slope degradation. The correlation is clearer in areas with low slope roughness where surface erosion is dominant, whereas that in areas with high roughness is more complicated due probably to disturbance by frequent landslides.

Conclusions

In this study we computed stream gradient with different measurement scales, and the scale-dependent change in stream gradient was used to quantify local bedrock river morphology and to extract knickzones. Using a coarser DEM, relatively large features such as knickzones were identified, while with a finer DEM, small-scale features such as small knickpoints were identified.

The method introduced here will be applied to multiple scale landforms of mountain bedrock rivers to address the processes of their morphological changes. For instance, with coarser DEMs such as SRTM and GDEM, global characteristics of bedrock river morphology would be examined, while finer DEMs at submeter-scale resolution permit the investigation of much smaller riverbed morphologies such as step-pools and large cobble accumulations.

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