

Valley Density as a Geomorphic Control on Rainfall-Induced Shallow Landslides in Japan

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Abstract: Shallow landslides triggered by intense rainfall are a common geomorphic phenomenon, and their occurrence is largely controlled by local topography including valley incision. We refined a plan curvature-based method to extract valleys from 10–20 m digital elevation models (DEMs) and evaluate the relationship between valley density and landslide source areas associated with recent heavy rainfall events. Valleys were extracted by a contour crenulation method with thresholds corresponding to contour inflection angles of $<90^\circ$, and drainage lines were generated using the D8 flow direction algorithm. Seven rainfall-induced landslide events across Japan were investigated, with landslide scars delineated using post-disaster aerial photographs. Grid-based analyses were conducted at multiple resolutions for regional-scale evaluation; we then focused on 1 km grids. The results show a positive correlation between valley density and landslide area at a grid scale of 1 km, with R^2 values of 0.53–0.90 across different regions. In this study, hilly terrain with valley densities of $\sim 4 \text{ km/km}^2$ is expected to produce 1000–2000 m^2 of shallow landslide area per km^2 during a single disaster event. These results highlight valley density as a robust indicator for assessing rainfall-induced landslide susceptibility.

Keywords: Rainfall-induced landslide, Valley density.

Introduction

Valleys and their heads tend to accumulate surface water and groundwater, where shallow landslides comprising soil and weathered rock on bedrock often occur during heavy rainfall. The spatial distribution of valleys can thus regulate the occurrence of rainfall-induced shallow landslides, and quantitative evaluation of this relationship is important for identifying safer areas at a regional scale.

Valleys are represented on topographic maps or digital elevation models (DEMs) as continuous lines extending downstream from their heads. In topographic interpretation, valley lines are drawn along the cusps of contours, and upstream terminations are determined by the contour inflection angle (Mark, 1983; Oguchi, 1997). In contrast, DEM-based approaches often employ contributing area or local curvature thresholds.

We refined a plan curvature-based extraction method to enable its application to different cell sizes and extracted valleys across the Japanese Islands. We then compared valley density with areas of shallow

landslides triggered by recent heavy rainfall in Japan to evaluate geomorphic controls on landslide occurrence.

Methodology

Valley heads and downstream drainage networks were extracted from the 10 m DEM published by the Geospatial Information Authority of Japan (GSI) using ArcGIS. For raster data with 10 m cells and aggregated to 20 m cells, plan curvature and slope were calculated using a 3×3 cell neighborhood (Zevenbergen and Thorne, 1987). Valley heads were assumed to occur where the slope was $> 4^\circ$. Cells where the plan curvature multiplied by the cell width was less than -2 were defined as valley cells, corresponding to contour inflection angles of $< 90^\circ$. These cells were converted to polygons, and continuity was assessed by retaining valley regions with areas of ≥ 6 cells, or regions of ≥ 3 cells that were located within two cells along the steepest slope direction. In this way, first-order valleys and their heads were extracted. Drainage networks were generated with the fill function, followed by D8 flow direction analysis, and some downstream drainage lines were adjusted to match contemporary human-modified channels using the GSI hydrography dataset.

Seven rain-induced landslide events in Japan were analyzed (Table 1). Landslide source and depositional areas were delineated using post-disaster aerial photographs taken by the GSI and digitized in ArcGIS. Pre-disaster imagery from Google Earth was used to confirm that the mapped sites corresponded to new landslides. The bedrock geology of the survey areas is granite in Kumano, Hiroshima, Murakami, and Marumori, accretional prisms in Nanyo, sedimentary rock in Noto, and both granite and metamorphic rock in Asakura.

The relationship between landslide area density and valley density was investigated as follows. The observed areas were divided into rectangular grids, areas of intense rainfall were selected, and hilly terrain and alluvial fans were identified using a landform classification map with 7.5° grid cells (Wakamatsu and Matsuoka, 2013). For each grid cell, the total valley length and landslide source area were calculated and divided by the grid area to obtain valley and landslide densities. First, grid sizes of 100 m, 250 m, 500 m, and 1

km were tested in Hiroshima to evaluate the scale at which valley density influenced landslide area. Then, landslide and valley densities were measured using 1 km grid cells in all seven regions, and relationships were examined by plotting the data.

Table 1, Surveyed landslide disasters in Japan

	Disaster area	Landslide event	Rainfall measurement
1	Kumano region	Kii Peninsula, Sep. 2011	250–470 mm / 24h
2	Asakura	North Kyushu, July 2017	200–280 mm / 3h
3	Hiroshima	West Japan, July 2018	>250 mm / 24h
4	Nanyo region	West Japan, July 2018	400–950 mm / 72h
5	Marumori	East Japan, Oct. 2019	200–270 mm / 3h
6	Murakami	Nigata, Aug. 2022	>400 mm / 24h
7	Noto	Noto Peninsula, Sep. 2024	120–180 mm / 3h

Results

The valley density is > 3 km/km² in the Kyushu and Chugoku regions, and lower in the Tohoku region and Hokkaido (Figure 1). High valley densities generally occur in mountainous areas underlain by weathered granite.

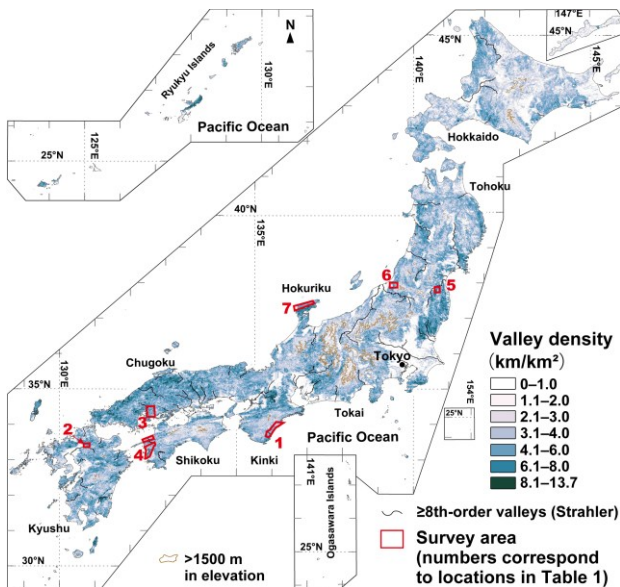


Figure 1, Valley density throughout the Japanese Islands.

The correlation between valley density and landslide area density is stronger with increasing grid size (Figure 2). In Hiroshima, the proportion of grid cells with landslide areas of > 0.1% shows a weak relationship with valley density at grid sizes of ≤ 500 m, but a positive correlation at a grid size of 1 km.

Analysis of the other six regions at a 1 km grid scale also shows that landslide area increases with valley density. Linear regressions yielded R² values of 0.90 (Marumori), 0.85 (Nanyo and Hiroshima), 0.68 (Asakura), and 0.53 (Noto and Kumano). Landslide areas were about ten times larger in Asakura and about twice as large in Noto than in the other regions, indicating that many failures occurred outside valley zones. On the Noto Peninsula, ground fissures that formed in association with the 2024 Noto earthquake 9 months earlier likely contributed to landslide initiation,

whereas in Asakura, the 2016 Kumamoto earthquake 15 months earlier may have had a similar effect.

Although direct comparison of absolute landslide areas among the individual cases is limited by variations in rainfall, previous disasters, and geology, each case demonstrated a consistent trend: a doubling of valley density is generally associated with a doubling of landslide source area.

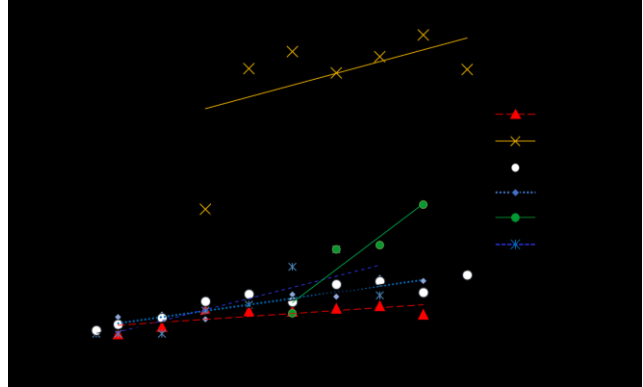


Figure 2, Valley density versus the mean percentage of landslide area within grid cells.

Conclusion

We derived hydrographic maps for Japan from 10–20 m DEMs and found that valley density in 1 km grid cells correlates significantly with rain-induced landslide area.

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