Global Polygons For Terrain Classification Divided Into Uniform Slopes And Basins

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Abstract

Global terrain classification data have been used for various issues that are known to be related to topography, such as estimation of soil types, estimation of Vs30, and creation of seismic hazard maps. However, due to the resolution of the DEMs used, the terrain classification data from previous studies could not discriminate small landforms, such as narrow valley bottom plains, and small-rises within the plains. We created a global polygon dataset of the shapefile format divided into uniform slopes from slope gradients and HAND (height above the nearest drainage) calculated using the 90m spatial resolution MERIT DEM, and combined this data with the unit catchments of MERIT-Basins. This dataset contains the calculated terrain measurements (slope gradient, HAND, surface texture, local convexity, Sinks) and polygon areas as attributes, as well as the ID number of the MERIT-Basins' unit catchment. In addition, the results of k-means clustering using slope gradient, HAND, and surface texture, which can be joined with the dataset as a simple terrain classification, are also available. This dataset can be used as a proxy and is expected to contribute to the modeling and estimation of various points that are known to be related to topography.

Introduction

One of the goals of geomorphometry is to use terrain measurements, i.e., physical quantities such as slope gradient, calculated from Digital Elevation Models (DEMs) to model and estimate various issues that are known to be related to topography, such as landslide risk, ground shaking susceptibility, and soil types. Quantitatively zoned terrain data is useful for interpolating and mapping various measurements known to be correlated with topography.

In the past, it was discovered that terrain classification data similar to man-made geomorphological maps could be created by combining terrain measurements calculated from DEMs (Iwahashi, 1994; Iwahashi and Kamiya, 1995). At that time, it was noticed that the combination of slope gradient and a valley density parameter (later organized as the surface texture; Iwahashi and Pike, 2007) could be used to classify broad terrain types such as mountains, volcanic areas, hills, plateaus, and plains, and that the local convexity could be used to classify intermediate terrain types such as terraces and fans. From this context, two types of global terrain classification maps, cell-based and polygonal, were produced from 1km spatial resolution SRTM30 (Iwahashi and Pike, 2007) and 280m MERIT DEM (Iwahashi et al., 2018). The terrain classification data given, and/or the creation method, are used or recommended as materials for estimating soil types (European Commission - DG JRC, 2008), for the estimation of Vs30 (average shear wave velocity for the top 30 m; a proxy of ground vulnerability to earthquakes) (Yong et al., 2012; Mori et al., 2020, etc.), or for seismic hazard mapping (Irsyam et al., 2017). There is a strong need for this type of data to estimate ground strength and soils. However, due to the resolution of the DEMs used, the terrain classification data from these previous studies could not discriminate narrow valley bottom plains or small-rises within the plains. The use of higher resolution DEMs was necessary for improvement, but it was thought that automatic classification would be more difficult with higher resolution DEMs because artificial steep cliffs in heavily man-made altered plains or unevenness of accuracy would become more

apparent. To accommodate the increasing resolution of DEMs and to produce more practical data, Iwahashi et al. (2021) introduced HAND (Height Above the Nearest Drainage; Rennó et al., 2008) as an additional parameter for the extraction of small-rises in plains. Iwahashi et al. (2021) conducted a terrain classification for the whole of Japan using a 30m DEM, aiming to achieve a terrain classification that reflected the ground vulnerability for various slopes from alluvial plains to mountainous areas, and that had both geomorphological and geotechnical classifications without major contradictions.

While basically following the method of Iwahashi et al. (2021), the data in this paper were created by calculating terrain measurements from the global 90m DEM of MERIT DEM (Multi-Error-Removed Improved-Terrain DEM; Yamazaki et al., 2017) and then by dividing the area into regions to create polygon data as material for creating terrain classification maps. As a new attempt, MERIT-Basins (Lin et al., 2019), which is unit catchment data calculated from MERIT DEM, was combined with polygon data which was segmented as uniform slopes and designed so that the uniform slopes are divided by the ridge lines of unit catchments. This is to alleviate the problem of region segmentation in the previous studies and to allow users to combine the locations of upstream and downstream catchments in MERIT-Basins as polygon attributes. This process is expected to make it easier to extract data for each catchment area and to assess the connection between upstream and downstream.

Construction And Content

2.1 Materials

2.1.1 DEM

The 3-arc-second grid MERIT DEM v1.0.3 (based on Yamazaki et al., 2017) was used as the main material. MERIT DEM was developed by merging several baseline DEMs, mainly the Shuttle Radar Topography Mission 3 arc-second DEM (SRTM3) ver. 2.1 (National Aeronautics and Space Administration: NASA) and the AW3D-30m DEM ver. 1 (Japan Aerospace Exploration Agency: JAXA).

2.1.2 Region partitioning and interpolation of DEMs

It was difficult to process the global DEM with a resolution of 3-arc-second grid data in one calculation due to system performance, and the usability of the resultant data was expected to be poor. Therefore, the polygon data of delimitation was created and defined as regions for terrain measurements. We used the basin edges of MERIT-Basins (Lin et al., 2019) or the sea to divide the global area into 67 regions (Fig. 1).

The DEMs within each region were combined and projected, then transformed into the Lambert Azimuthal Equal Area (WGS84) to produce a 90m DEM with the coordinates near the center of the land area as the central meridian. Two resampling methods, the nearest neighbor method and the bilinear method, were used to create interpolated DEMs.

2.1.3 Masking data of NoData

To avoid underestimating the terrain measurements in areas near water where the slope changes rapidly, such as where a mountain meets a lake, it is necessary to create mask data for those water areas and use it as a mask (NoData) for the DEM when calculating the terrain measurements. In a previous study (Iwahashi et al., 2018), the water part of the land cover classification of GlobCover 2009 (Bontemps et al., 2013) was used, but the resolution was coarse at about 300m, and because the source was satellite imagery, blank areas due to clouds were unavoidable in the independent peaks of remote islands. In this study, HydroLAKES (Messenger et al., 2016) were used for masking lakes. HydroLAKES is a global polygon data of lakes larger than 10 ha. Some parts that required modification were manually modified and used, although only within Japan. HydroLAKES does not include brackish lakes or large rivers that should be NoData parts in this study, so supplementary data was necessary. Initially, we considered using land cover classification based on satellite imagery, but it was difficult to identify reclaimed land in shallow waters and islands in coral reefs. Therefore, we used the Code2 major rivers and water sections extracted from the OSM Water Layer. The OSM Water Layer (Yamazaki et al., 2017; downloaded from the IIS U-Tokyo webpage: http://hydro.iis.u-tokyo.ac.jp/~yamadai/OSM_water/) was a published dataset which was created by extracting water-related data from OpenStreetMap.

This masking data was used as NoData masks to minimize errors in areas where the slope changes rapidly. This data does not necessarily reflect the actual extent of the water areas, because the accuracy of the water-related data of OpenStreetMap is not authorized, except in areas where the data of mapping agencies are used as the original data, there is a large difference in the accuracy of the data in different areas and the treatment of the intertidal zone is probably not consistent.

2.1.4 Supplementary data

MERIT-Basins' vector hydrography (based on MERIT-Hydro v1.0) unit catchment shapefiles (Lin et al., 2019) was used as auxiliary thematic data for the segmentations.

2.2 Method

2.2.1 Terrain measurements

The terrain measurements used in this study basically followed the geometric signatures of Iwahashi et al. (2021). The 90m DEMs were used to calculate the terrain measurements as attributes shown in Table 1.

Table 1
Terrain attributes and their calculation methods

Attribute	Calculation method	Description
InSLOPE	$\ln(\text{SLOPE} + 1)$ SLOPE: slope gradient (degrees) calculated from the 90m DEM interpolated by the bilinear option	SLOPE was calculated within 3 by 3 cells windows, using QGIS 3.14, by the Horns method
InHAND	$\ln(\text{HAND} + 1)$ HAND: Height Above the Nearest Drainage (m)	HAND was calculated by the method of Yamazaki et al. (2012) and Yamazaki et al. (2019).
TEXTURE	Density within a 10-cell radius of pits and peaks obtained by the difference between the Original DEM and the 3x3 median filtered DEM. Original DEM: the 90m DEM interpolated by the nearest-neighbor option	The surface texture of Iwahashi and Pike (2007). TEXTURE was calculated by the "terrain surface texture" tool of SAGA (Conrad, 2012a) in QGIS 3.4 (Threshold: 5 m, radius: 10 cells, no distance weighting)
CONVEXITY	Density within a 10-cell radius of convex points obtained by processing the DEM with a 3x3 Laplacian filter. Original DEM: the 90m DEM interpolated by the nearest-neighbor option	The local convexity of Iwahashi and Pike (2007). CONVEXITY was calculated by the "terrain surface convexity" tool of SAGA (Conrad, 2012b) in QGIS 3.4 (Threshold: 1 m, radius: 10 cells, no distance weighting)
Sinks	Sinks is the following region: $((\text{Filled DEM}) - (\text{Original DEM})) > 0$ Original DEM: the 90m DEM interpolated by the bilinear option Filled DEM: DEM with the surface depressions (sinks) filled in	Filled DEM was calculated by the "Fill Sinks (Wang & Liu)" (Wang and Liu, 2006) tool of SAGA in QGIS 3.4

For the HAND calculation, Iwahashi et al. (2021) used TauDEM (Tarboton, 1997; 2005). However, in this study, due to the system cost associated with the increase in data volume, we applied the HAND calculation method of MERIT Hydro (Yamazaki et al., 2019), a product that has already been hydrologically corrected, and created it from MERIT DEM. MERIT Hydro uses a unique correction algorithm (Yamazaki et al., 2012) to perform hydrological elevation correction. It is a method that calculates the flow direction from global elevation data and water body data, and then minimizes the amount of topographic correction while maintaining the condition that the downstream elevation is not

higher than the upstream elevation. Unlike HAND calculated by TauDEM used in Iwahashi et al. (2021), this data did not go through the fill surface depressions (sinks) process first, so it cannot extract lowlands by itself. The fill sinks tool of Wang and Liu (2006) was used separately to extract Sinks (Table 1) and place attributes on the polygon data. The method of Wang and Liu (2006) can fill surface depressions relatively fast, even for large data of this study. Sinks were extracted by the difference between the filled DEM and the original DEM.

Surface texture and local convexity are very noise-sensitive parameters. Although the MERIT DEM largely mitigates the unevenness of the source DEMs, the effect of the difference of baseline data or the stripe noise in MERIT DEM became apparent, especially in high latitude regions and deserts (Iwahashi et al., 2018). This problem also remains in the 90m spatial resolution MERIT DEM. The intensity to which such heterogeneity becomes apparent varies with the resolution of DEMs. The raster images from the terrain measurements in this study show different patterns to the results from Iwahashi et al. (2018) at a 280m resolution.

In the case of calculating TEXTURE (Table 1), by setting the threshold for extracting ridges and valleys during the calculation to 5 m, we were able to eliminate the effects of unevenness except in a few areas centered on deserts, while retaining useful information such as the distinction between volcanic and non-volcanic slopes. For local convexity, the noise could not be eliminated by increasing the threshold for the extraction of convex points, and expanding the window size for density calculation was an option (Iwahashi et al., 2021). However, in such a case, the overall disadvantage was high, considering the balance between the loss of information commensurate with the 90m resolution and the fact that local convexity is an auxiliary parameter. Therefore, CONVEXITY (Table 1) was finally decided to calculate the density with the default 10 cells radius.

2.2.2 Detection of areas containing significant noise

As mentioned earlier, in some areas of CONVEXITY and a few areas of TEXTURE, the unevenness of the source DEMs were reflected. Many of these “noise” regions (hereafter Noise) are along orbital stripes, and the regions which are distributed in TEXTURE alone are in deserts. In addition, Noise or low-values in InSLOPE (Table 1) is also observed in the region of deserts or in parts of ice sheets. Within the CONVEXITY, TEXTURE, and InSLOPE images used for classification in this study, Noise polygons were created as the portion of the image that can be significantly identified by visual inspection of the maximum-minimum stretch. The ice sheet areas were also identified as Noise using InSLOPE images and World Imagery, which is provided as a base-map in ArcGIS Online (ESRI).

2.2.3 Segmentation

Using the raster data of terrain measurements and supplementary thematic data, the regions were divided into uniform slopes, and polygon data were created. The segmentation method was the same as Iwahashi et al. (2021). The multiresolution segmentation (Baatz and Schäpe, 2000) method implemented in eCognition (Trimble) was used to segment the data under the following conditions. TEXTURE and CONVEXITY were not used for the segmentation.

Weight $\ln\text{SLOPE}:\ln\text{HAND} = 2:1$,

Scale parameter = 10, Shape parameter = 0.

The unit catchment of MERIT-Basins (Lin et al., 2019) and the Noise polygons (2-2-2) were used as thematic layers. Therefore, the final polygons are divided by the catchment areas as well as the terrain features. After the regional data was divided into regions, it was output to shapefile format data with the representative values for each terrain measurement contained in the polygon.

For Australia, which has a very large amount of data, this work was divided into two portions due to the capacity of the system in use. The boundaries of unit catchments of MERIT-Basins were used for the division.

2.2.4 Regional k-means classification

Each of 67 regions was classified by k-means clustering (MacQueen, 1967). Standardized $\ln\text{SLOPE}$, $\ln\text{HAND}$, and TEXTURE were used for the calculations, following Iwahashi et al. (2021). The calculations were performed using SPSS v26 (IBM), with the number of clusters set to 15 and 40, the convergence criterion set to 0, and the maximum number of iterations set to 999. The clustering was also done in batches for the areas where polygons were created by dividing the area (Fig. 1, 56 – 1 and 56 – 2).

The 15 clusters data is intended to be used as a simple terrain classification map of the region. The 40 clusters data is intended to be grouped by users according to local conditions, therefore the number of clusters was set to be large. For some basins with a large number of cases (Figs. 1, 62 and 26), the calculation did not converge at the maximum number of iterations (999) for 40 clusters. However, the maximum absolute coordinate change for any given center was small, 0.001 for the 40 clusters of Amazon River basin (Fig. 1, 62), which was the largest.

Results And Discussion

3.1 Polygon data

The polygon data are stored in the shape file format, and the attributes include the ID number (polyID), the average values of terrain measurements in the polygon ($\ln\text{SLOPE}$, $\ln\text{HAND}$, TEXTURE , CONVEXITY), the mode value of Sinks, the code number of Noise, and the COMID number of MERIT-Basins. The regional clusters (40, 15) are provided as a separate DBF file. Details of the data are as follows.

1) Properties of the original polygon data (shapefile dataset, Poly_XX (XX: the index number))

polyID: ID number for each polygon

$\ln\text{SLOPE}$ (calculated as in Table 1): average value

$\ln\text{HAND}$ (calculated as in Table 1): average value

TEXTURE (calculated as in Table 1): average value

CONVEXITY (calculated as in Table 1): average value

Sinks (calculated as in Table 1): (0) The majority of the area within a polygon is not sinks. (1) The majority of the area within a polygon is sinks.

Noise (manual interpretation; datasets with apparent noise only): (0) There is no apparent noise or ice sheet. (1) There is apparent noise on CONVEXITY. (2) There is apparent noise on TEXTURE and CONVEXITY. (3) Apparent ice sheet. (4) There is apparent noise on TEXTURE. (5) There is apparent noise on InSLOPE. (6) There is apparent noise on InSLOPE, TEXTURE, and CONVEXITY. * (0) to (2) are found in a wide range of areas; (3) is found in the polar regions; (4) to (6) are found only in desert areas.

COMID: ID number for each unit catchment of MERIT-Basin (Lin et al., 2019). Polygons with '-99999' are the regions which MERIT-Basin does not cover.

2) Properties of the cluster file (dBASE IV, Cluster_XX)

polyID: ID number for each polygon

ZInSLOPE: standardized InSLOPE. Noise areas (2) to (6) are not included.

ZInHAND: standardized InHAND. Noise areas (2) to (6) are not included.

Ztexture: standardized TEXTURE. Noise areas (2) to (6) are not included.

Cluster15: Cluster number by k-means clustering of 15 categories using standardized InSLOPE, InHAND and TEXTURE with each polygon area as the weight. The cluster number (1–15) is not common to other basins. Noise areas (2) to (6) are not included.

Cluster40: Cluster number by k-means clustering of 40 categories using standardized InSLOPE, InHAND and TEXTURE with each polygon area as the weight. The cluster number (1–40) is not common to other basins. Noise areas (2) to (6) are not included.

3) Properties of the cluster convergence values (CSV, XX_convergence_values_cluster15, XX_convergence_values_cluster40)

Convergence values for each clustering of ZInSLOPE, ZInHAND, Ztexture.

3.2 Usage of the dataset and notes

The clustering result (CSV) can be joined with the shapefile (Poly_XX) using GIS software with polyID as the key. The result of joining itself is a simple terrain classification map (Fig. 3). As shown in Iwahashi et al. (2021), the 40 clusters can be grouped by comparing them with existing thematic data and scatter plots of clustering convergence values to construct a terrain classification map. In areas where

CONVEXITY does not contain noise, it may be possible to use it to reclassify intermediate slopes, such as eroding unconsolidated terraces and alluvial fans, as in Iwahashi et al. (2021).

In continental regions, Sinks (Table 1) extracted by the “Fill Sinks (Wang and Liu)” tool using the 90m DEM cover a wide area of plains. Sinks are limited in the orogenic zone where alluvial fans develop, such as in Japan. It is unclear to what extent Sinks are related to water resources due to differences in climate and geology in different regions, but when combined with areas where HAND is small (blue areas in Fig. 4), they may be useful for environmental assessment. We provide users with both Sinks and InHAND (Table 1). The InHAND ($= \ln(\text{HAND} + 1)$) can be converted to HAND.

Since the shapefile dataset contains COMID (Lin et al., 2019) as a field attribute, it is considered possible to join attributes of information on the location of upstream and downstream of each catchment area contained in the MERIT-Basins’ river data (Lin et al., 2019) using COMID as a key. The relationship between upstream and downstream in the same unit catchment can probably be determined by the value of InHAND.

The notes for using the dataset are as follows. The DEM reflects the topography at the time of measurement. Therefore, the classification results are not likely to be the expected ground proxies for man-made altered areas such as reclaimed land or cut-and-fill areas. Since the Noise areas were designated visually, there is a possibility that there may be some oversight or overestimation.

In some areas of brackish lakes and large rivers, the center-line may not be NoData, but narrow polygons due to the OpenStreetMap used to extract these areas. These narrow polygons need to be removed before use. There are often small polygons at the confluences of valleys. These polygons coincide with the blank parts of MERIT-Basins and were caused by the combining of the segmented polygons and MERIT-Basins. Since the areas are very small, they do not have obvious influence on the clustering results.

Conclusions

In this study, we used terrain measurements (physical quantities such as slope) calculated using a 90m Digital Elevation Model (DEM) to create map data zoning slopes with similar shapes, i.e., similar properties. By using a hydrological parameter, HAND, we succeeded in extracting small-rises in the plains that were not captured in previous studies. We created data that can be combined with the existing database of catchment areas to add upstream and downstream information. The data, including the interim results, were made available on the website.

The results of similar previous studies have been used for various issues that are known to be related to topography, such as soil type estimation, estimation of Vs30, and creation of seismic hazard maps. In this study, we used an approximately 3 x 3 times finer DEM compared to the previous study, which used 280m grid DEMs, and the new parameter greatly improved the extractions of the small-rises of the plains, which is expected to make the estimation more accurate. In addition, since the data in this study is also

zoned for mountainous areas, it is expected to contribute to the modeling and estimation of hazards in mountainous areas, such as landslide hazards.

Abbreviations

DEM: Digital elevation model; GIS: Geographic information system; GSI Japan: Geospatial Information Authority of Japan; HAND: Height above the nearest drainage; IIS U-Tokyo: Institute of Industrial Science, The University of Tokyo; OSM: OpenStreetMap

Declarations

Availability of data and material

The datasets supporting the conclusions of this article are available in the GSI Japan website, [<https://gisstar.gsi.go.jp/terrain2021/>].

Competing interests

The authors declare that they have no competing interest.

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Authors' contributions

Jl proposed the topic, conceived and designed the study, and developed and analyzed the data on terrain classification. DY aggregated and prepared the 90 m DEM and HAND. All authors read and approved the final manuscript.

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Endnotes

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Figures

Figure 1

Index map of the region partitioning. Since the area including Australia has a large amount of data, the output data is divided into two parts using the boundaries of the unit catchments.

Figure 2

Region segmentation around the Kanto Mountains (Japan). The blue lines are the uniform slope segmentation lines by InHAND and InSLOPE, and the pink lines are the boundaries of unit catchments of MERIT-Basins. The color tones are R: InSLOPE, G: InHAND, and B: TEXTURE in this image.

Figure 3

The Amazon River basin, color-coded in 15 clusters.

Figure 4

The areas of Sinks in the Australian continent with HAND.

Supplementary Files

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