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Supplementary material

Using the Spatiotemporal Hotspot Analysis and Multi-Annual Landslide Inventories to Analyze the Evolution and Characteristic of Rainfall-Induced Landslide at the Sub-Watershed Scale in Taiwan

Chunhung Wu

1. Detailed Explanation of Geological Settings in Taiwan

The distribution of geological settings in Taiwan is shown in Figure 2 in the manuscript. Table S1 in the Supplementary Materials shows a detailed explanation of geological settings in Taiwan.

Table S1. Detailed information of geological settings in Taiwan.

Age	Stratigraphical Formation	Per. (%)
Recent	Alluvium	8.83
Recent	Raised Coral Reef	0.73
Pleistocene	Basalt	4.08
Pleistocene	Hengchun Limestone	0.85
Pleistocene	Lateritic Terrace Deposits	6.57
Pleistocene	Terrace Deposits	21.67
Pliocene - Pleistocene	Lichi Formation, Kenting Formation	0.97
Pliocene - Pleistocene	Pinanshan Conglomerate	0.18
Pliocene - Pleistocene	Toukoshan Formation and its equivalents	5.30
Pliocene	Chinshui Shale and its equivalents	2.68
Pliocene	Cholan Formation and its equivalents	3.65
Miocene - Pleistocene	Andesite	2.25
Miocene - Pleistocene	Andesitic Pyroclastics	1.52
Late Miocene - Pliocene	Takangkou Formation, Chimei Formation	1.89
Late Miocene	Sanhsia Group and its equivalents	7.67
Middle Miocene	Juifang Group and its equivalents	7.49
Miocene	Lushan Formation	0.91
Early Miocene	Tuluanshan Formation	1.64
Early Miocene	Yehliu Group and its equivalents	5.72
Oligocene - Miocene	Aoti Formation	0.43
Oligocene - Miocene	Kankou Formation	1.40
Oligocene - Miocene	Tatungshan Formation	2.01
Eocene - Oligocene	Szeleng Sandstone	1.77
Eocene	Hsitsun Formation, Hsinkao Formation	0.37
Late Paleozoic - Mesozoic	Tananao Schist	4.02
Pleistocene	Tananwan Formation, Milun Formation	0.55
Pre-Tertiary	Quartz Porphyry	0.06
Pre-Tertiary	Serpentinite and Basic Igneous Rocks	0.37
Age unknown	Gabbro, Peridotite, Basalt, Serpentinite, Agglomerate(Mostly Exotic Blocks)	4.44

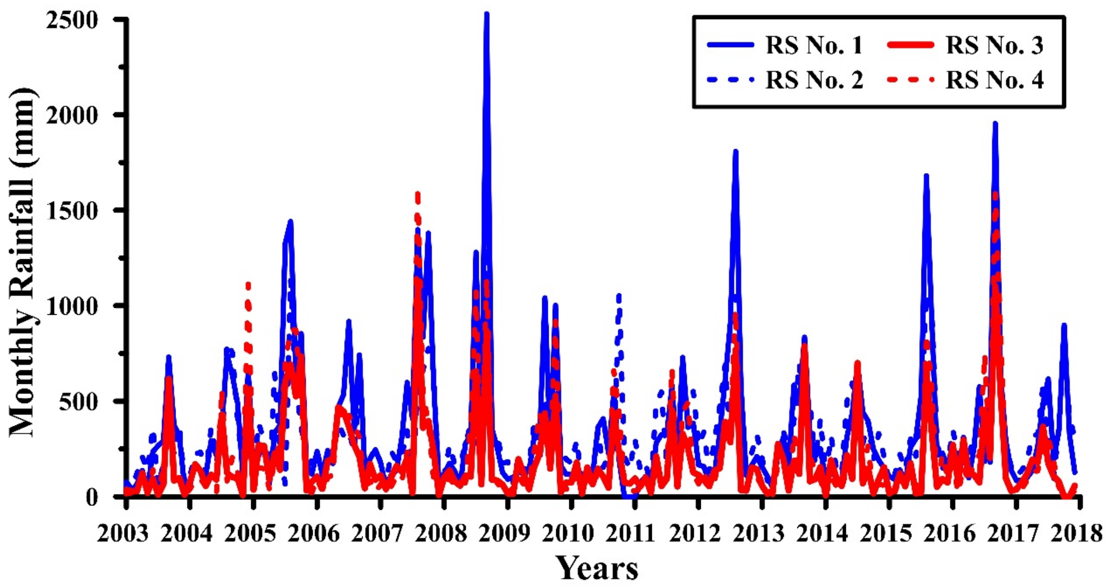
2. Detailed Explanation of 16 Rainfall Stations

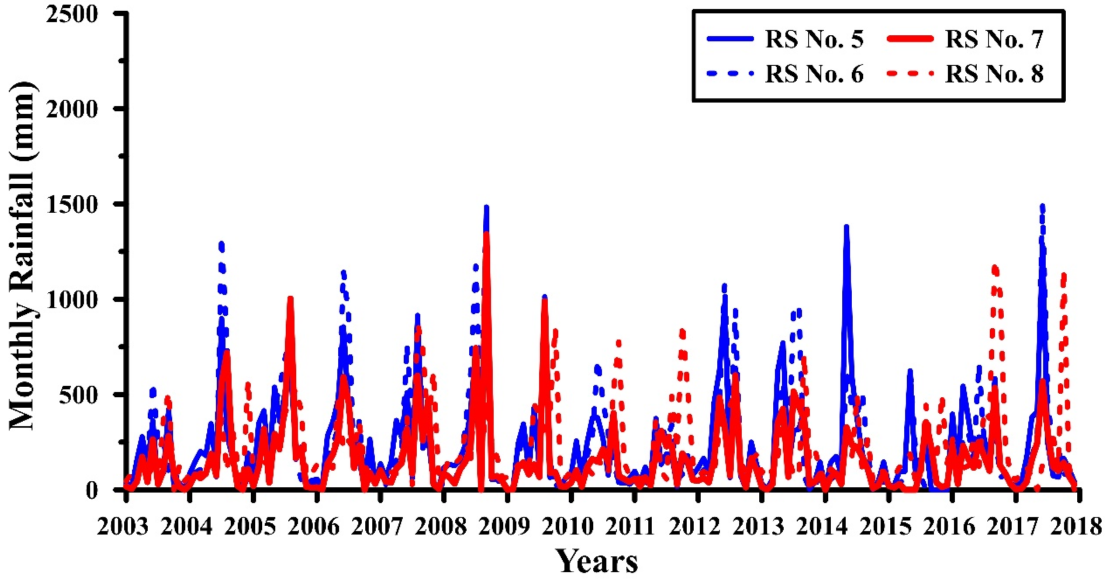
The detailed information of the 16 rainfall stations (Figure 1a in the manuscript) used in the study are described in Table S2 in the Supplementary Materials, and the temporal distribution of monthly rainfall in 2003–2017 and 2008–2017 are shown in Figure S1 in the Supplementary Materials.

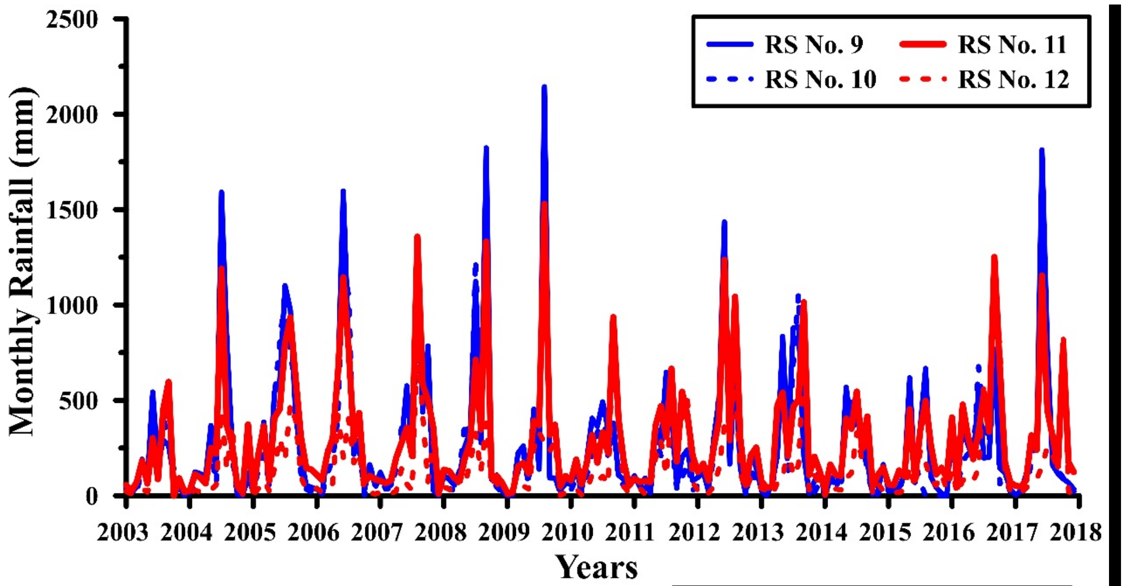
Table S2. Detailed information of 16 rainfall stations used in the study.

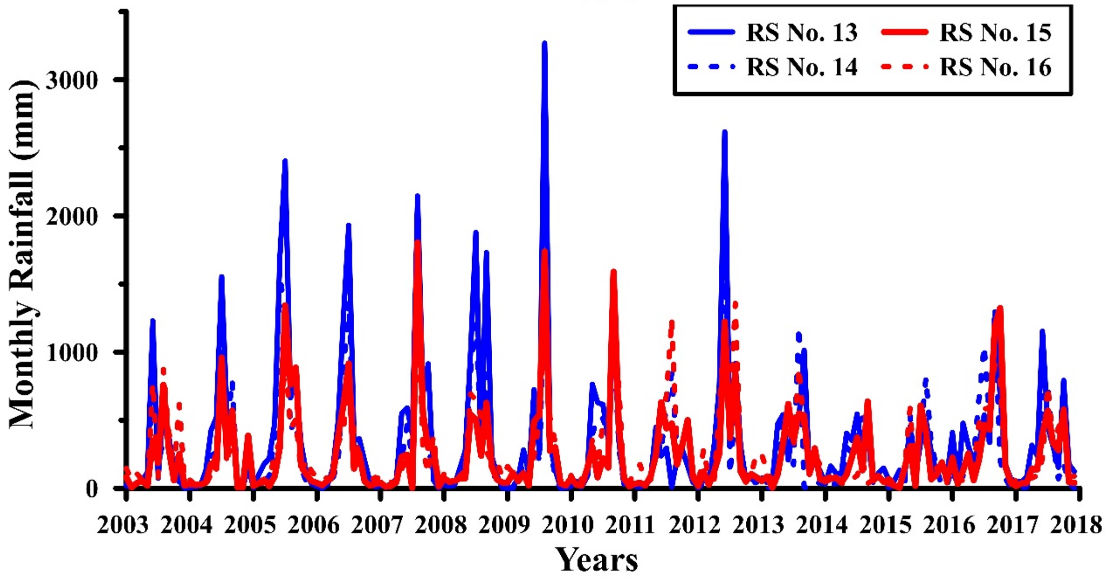
No.	Name	Elevation (m)	Temporal Distribution of Rainfall					
			2003–2017			2008–2017		
			Annual* (mm)	Rainy* (%)	Dry* (%)	Annual (mm)	Rainy (%)	Dry (%)
1	Taipingshan	1942	4261.3	78.7	21.3	4098.8	79.5	20.5
2	Tonghou	360	3797.0	66.8	33.2	3928.2	67.1	32.9
3	Luoshao	1260	2189.7	71.4	28.6	2047.9	71.4	28.6
4	Buluowan	675	2487.5	80.1	19.9	2413.9	81.1	18.9
5	Aowanda	1275	2715.2	70.7	29.3	2690.4	70.9	29.1
6	Jiufenershan	837	2778.2	82.9	17.1	2683.9	82.5	17.5
7	Kanaituowan	1700	1915.0	79.3	20.7	1833.5	78.0	22.0
8	Danong	183	2611.2	72.1	27.9	2669.5	72.7	27.3
9	Shenmu	1595	3360.8	82.2	17.8	3205.9	80.9	19.1
10	Ruili	1252	2935.4	86.9	13.1	2739.8	85.9	14.1
11	Xiangyang	2280	3573.3	77.2	22.8	3577.6	76.5	23.5
12	Chishang	289	1770.3	83.5	16.5	1838.3	83.9	16.1
13	Weiliaoshan	1006	4274.2	87.7	12.3	4008.1	84.2	15.8
14	Sandimen	105	3102.0	92.9	7.1	2996.1	92.3	7.7
15	Tjuabal	122	2980.4	84.6	15.4	2992.1	83.5	16.5
16	Binlang	242	3141.8	80.4	19.6	3259.6	81.2	18.8

Notes: [1] The annual means the average annual rainfall, the rainy means the ratio of average accumulated rainfall from May to October to the average annual rainfall, and the dry means the ratio of average accumulated rainfall from January to April and from November to December to the average annual rainfall.




RS No. 5
RS No. 7
RS No. 6
RS No. 8
Monthly Rainfall (mm)
0
500
1000
1500
2000
2500
2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Years


RS No. 9
RS No. 11
RS No. 10
RS No. 12
Monthly Rainfall (mm)
0
500
1000
1500
2000
2500
2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Years

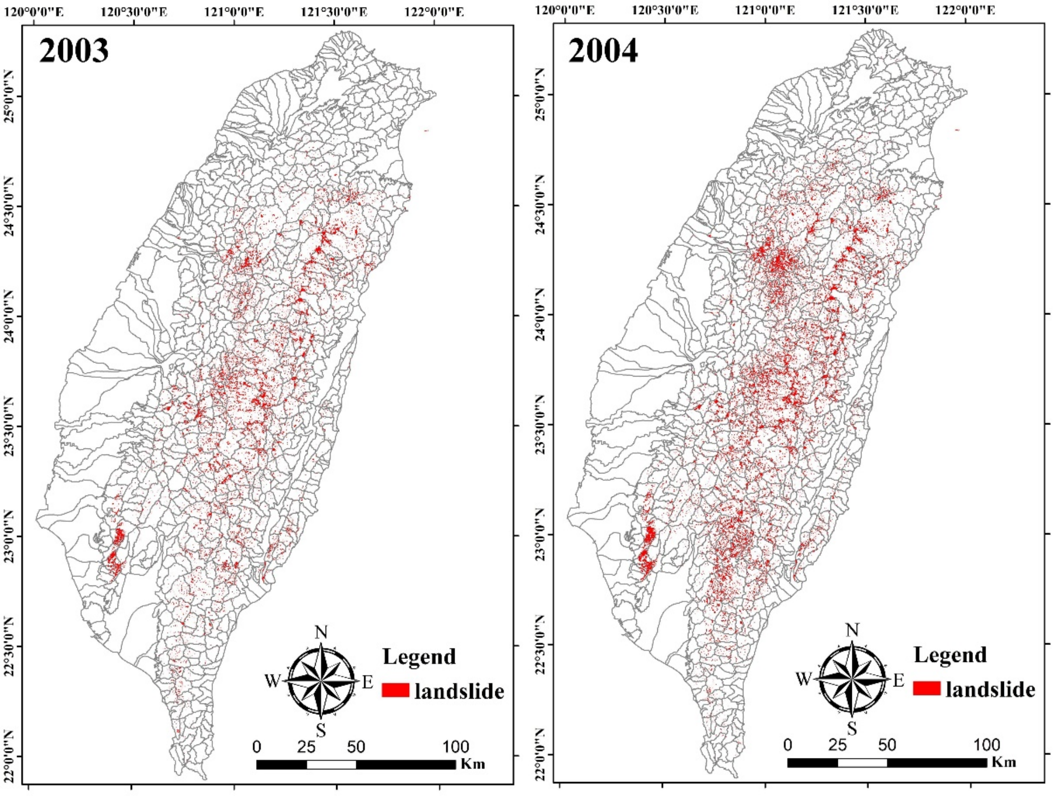

RS No. 13
RS No. 15
RS No. 14
RS No. 16
Monthly Rainfall (mm)
0
1000
2000
3000
2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Years

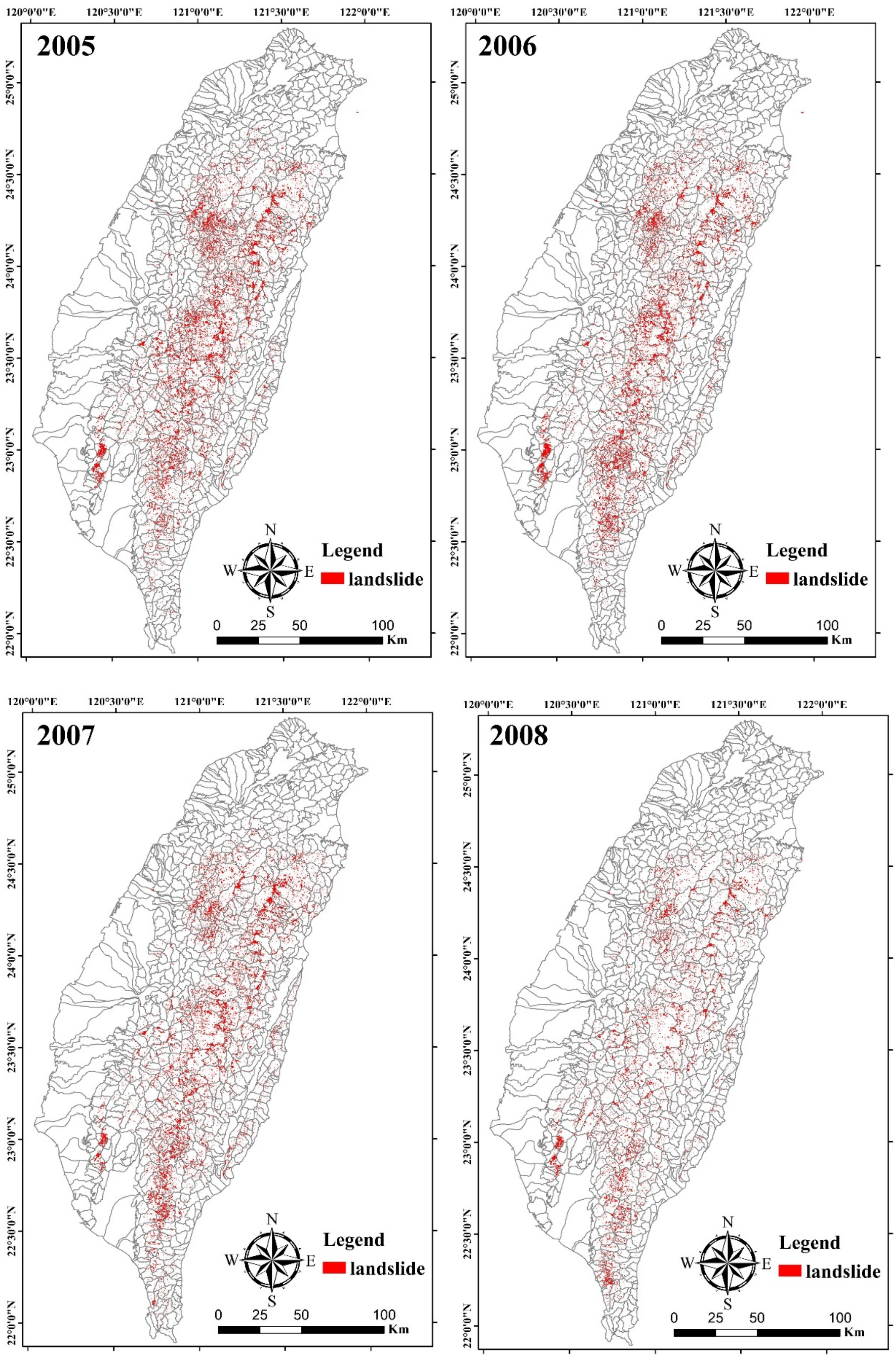
.

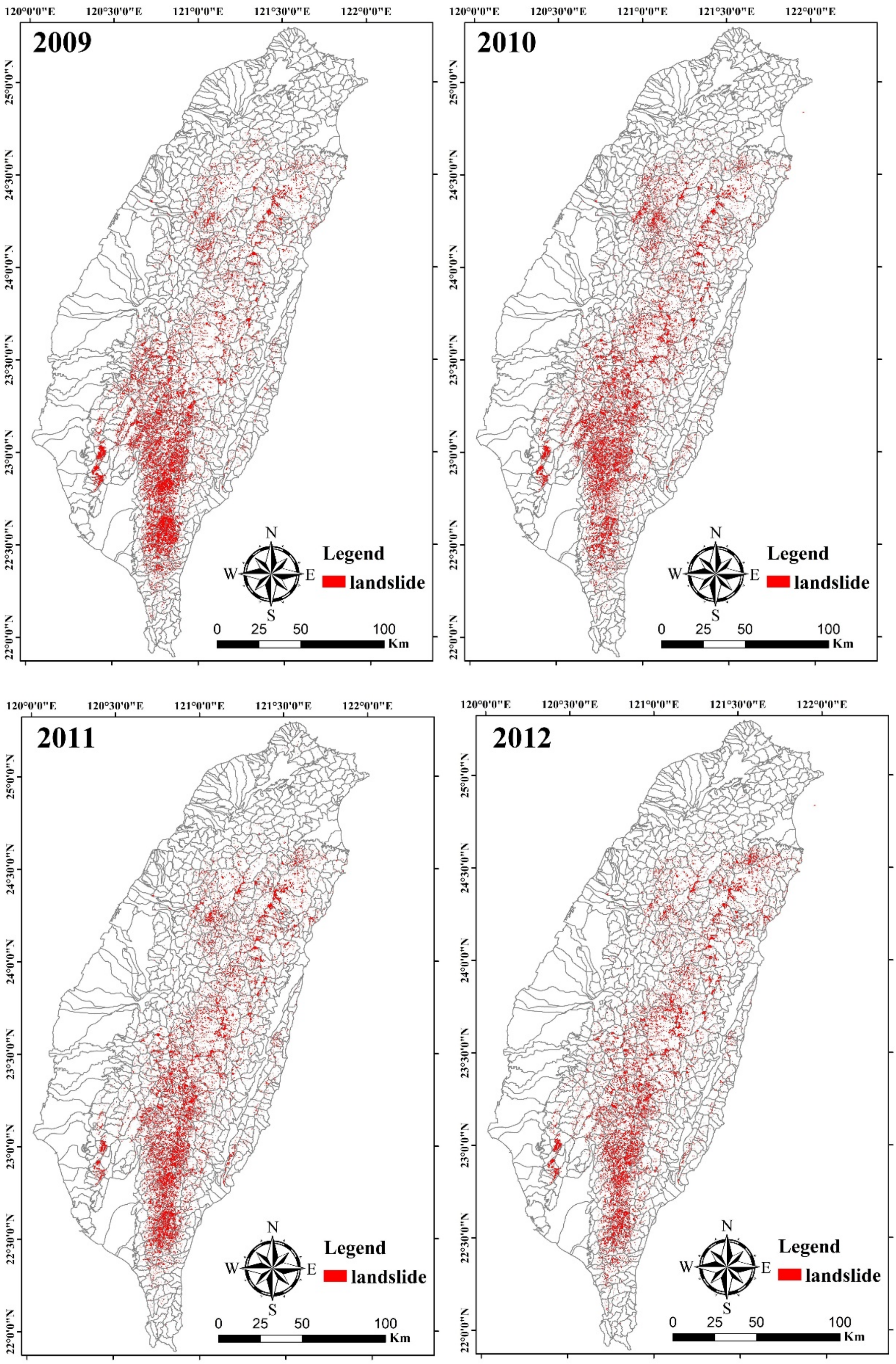
Figure S1. The temporal distribution of monthly rainfall in 2003–2017 collected from 16 rainfall stations.

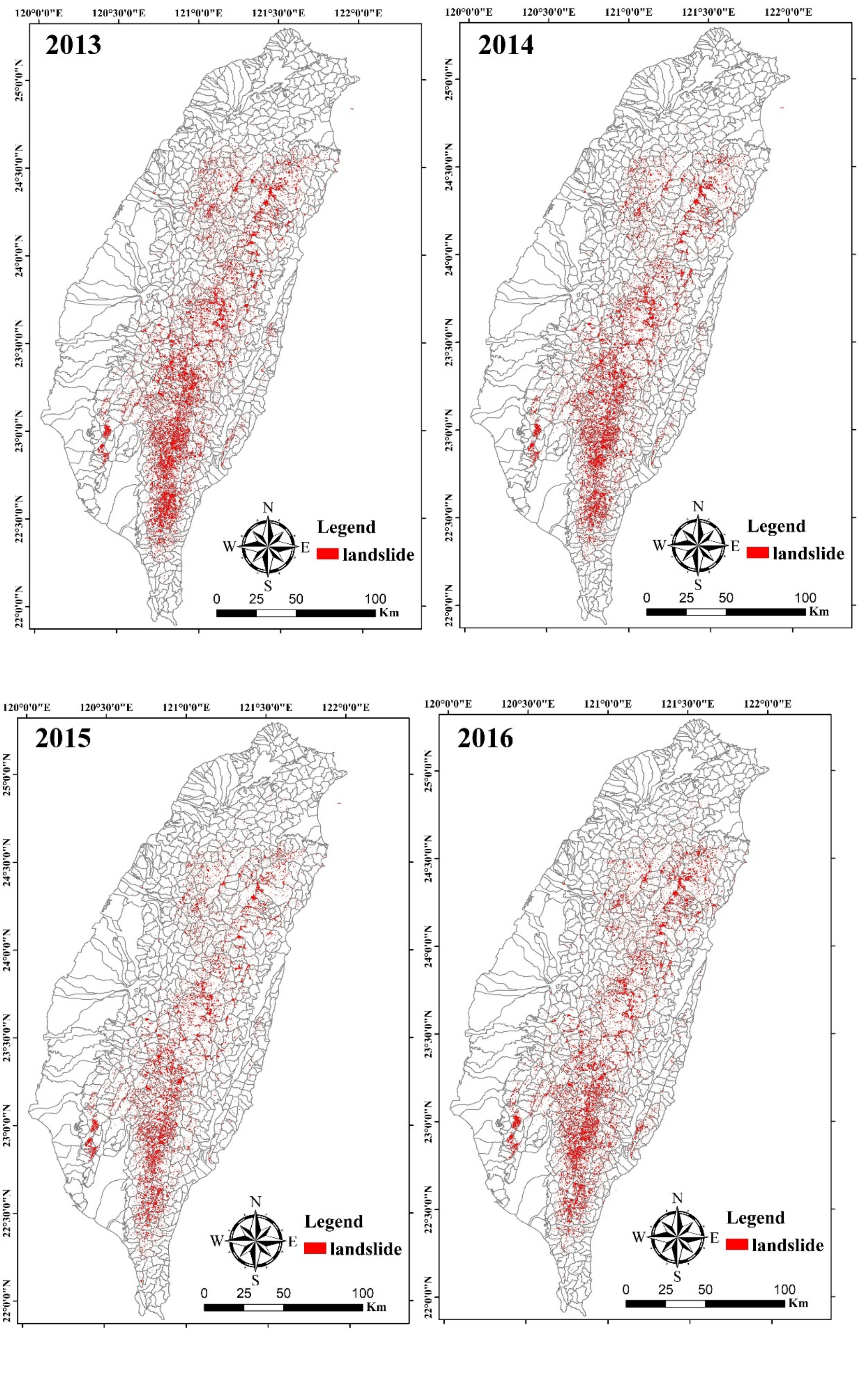
3. Annual Landslide Inventories in 2003–2017 in Taiwan

The annual landslide inventories in 2003–2017 in Taiwan were produced by Taiwan's Forestry Bureau. Formosat-2 imagery was used to produce the annual landslide inventories in 2003–2017 in Taiwan. The Formosat-2 imagery in January of next year was used as a basic image to delineate the polygon of landslide in this year. Formosat-2 imagery in January 2005, for example, was used to produce the annual landslide inventories in 2004. The preprocess of the Formosat-2 imagery, including the band-to-band co-registration, automatic orthorectification, and multi-temporal image geometrical registration, was produced using Formosat-2 automatic image processing system (Liu et al., 2007; Liu et al., 2009; Liu et al., 2009; Liu et al., 2019). After the preprocess of the Formosat-2 imagery, the Expert Landslide and Shaded Area Delineation System (ELSADS) was used to delineate the polygon of the landslide. The spatial resolution of the Formosat-2 imagery was 2–5 m, and the minimum area in the annual landslide inventories from 2003–2017 was 100 m^2 (Liu et al., 2019). The distribution of annual landslides in 2003–2017 is shown in Figure 2 in the Supplementary Materials.




2005
2006
2007
2008
120°0'0"E
120°30'0"E
121°0'0"E
121°30'0"E
122°0'0"E
25°0'0"N
24°30'0"N
24°0'0"N
23°30'0"N
23°0'0"N
22°30'0"N
22°0'0"N
Legend
landslide
N
S
W
E
0 25 50 100
Km


2009
2010
2011
2012
120°0'0"E
120°30'0"E
121°0'0"E
121°30'0"E
122°0'0"E
25°0'0"N
24°30'0"N
24°0'0"N
23°30'0"N
23°0'0"N
22°30'0"N
22°0'0"N
N
S
W
E
Legend
landslide
0 25 50 100
Km


2013
2014
2015
2016
120°0'0"E
120°30'0"E
121°0'0"E
121°30'0"E
122°0'0"E
25°0'0"N
24°30'0"N
24°0'0"N
23°30'0"N
23°0'0"N
22°30'0"N
22°0'0"N
N
S
W
E
Legend
landslide
0 25 50 100
Km

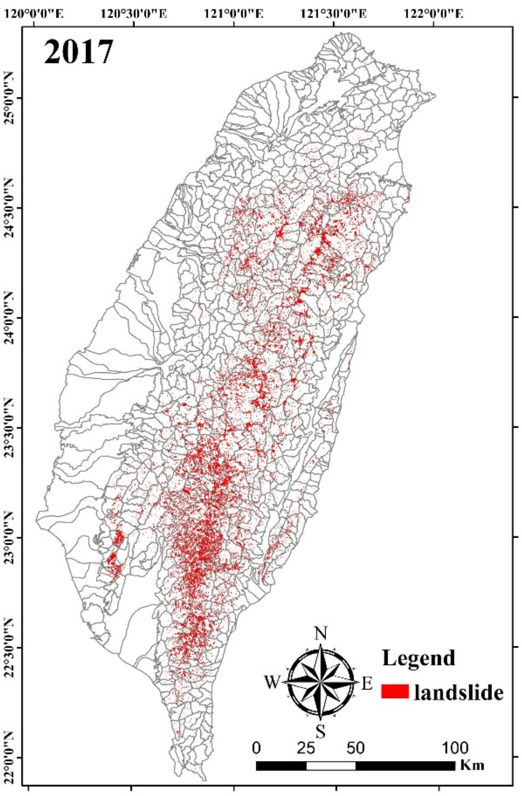


Figure S2. Distribution of annual landslide in 2003–2017 in Taiwan.

4. The Spatiotemporal Landslide Cube Model

The spatiotemporal hot spot analysis of landslide evolution in this study was based on the spatiotemporal landslide cube model. The concept of the spatiotemporal landslide cube model is shown in Figure 3 in the Supplementary Materials. The spatiotemporal landslide cube model was created based on the multiannual landslide inventories in 2003–2017 and the 839 subwatershed data in Taiwan. We estimated the landslide ratio in each subwatershed in each year from 2003–2017. The basic unit in the spatiotemporal landslide cube model is a subwatershed in Taiwan. Two spatiotemporal landslide cube models were created in the manuscript, including the 2003–2017 model and the 2008–2017 model. The 2003–2017 spatiotemporal landslide cube model contained the annual landslide inventories from 2003–2017, and there were 12,585 basic units, i.e., 839 (number of all subwatersheds) * 15 (years, from 2003 to 2017), in the 2003–2017 spatiotemporal landslide cube model. The 2008–2017 spatiotemporal landslide cube model contained the annual landslide inventories in 2008–2017, and there were 8390 basic units, i.e., 839 (number of all subwatersheds) * 10 (years, from 2008 to 2017), in the 2008–2017 spatiotemporal landslide cube model. The characteristic value in each basic unit is the landslide ratio in the subwatershed in a specific year from 2003 to 2017.

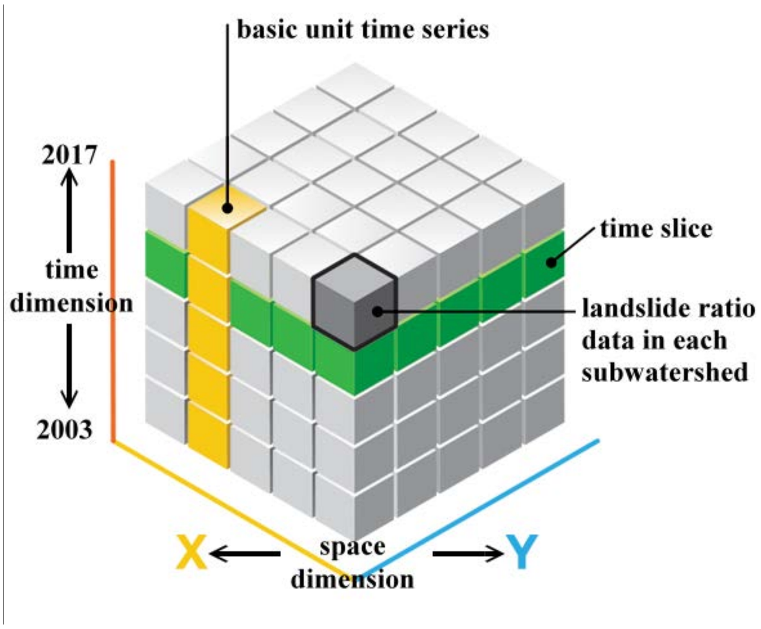


Figure S3. The concept of the spatiotemporal landslide cube model. (This is a revised figure, and the original figure is on the following website https://pro.arcgis.com/en/pro-app/latest/tool-reference/space-time-pattern- mining/emerginghotspots.htm)

5. Detecting or Measuring the Temporal and Spatial Trends of Landslide Ratio in the Spatiotemporal Landslide Cube Model

The Mann–Kendall statistic and the Anselin Local Moran's I index were used in this study to detect or measure the spatial and temporal trends of landslide ratios in the spatiotemporal landslide cube models.

The Mann–Kendall statistic was used to measure the temporal trend of the landslide ratio in a specific basic unit (a specific subwatershed) in the spatiotemporal landslide cube model. The Mann–Kendall statistic can detect the temporal trend of characteristic value (landslide ratio) in each basic unit, and the temporal trend means that the landslide ratio in a specific area has been increasing or decreasing over time.

The Anselin Local Moran's I index was used to measure the spatial clusters of characteristic values with high or low values, and the characteristic value in this study was the landslide ratio value in each basic unit. The analysis results using the Anselin Local Moran's I index included the local Moran's I value, the z-score, and the pseudo p-value. The local Moran's I index value shows the spatial cluster or outlier of a basic unit and its neighboring units. The positive value of local Moran's I index indicates that a basic unit has neighboring basic units with similarly high or low landslide ratios, and the negative value of local Moran's I index indicates that a basic unit had neighboring basic units with dissimilar high or low landslide ratio values. The z-scores and p-values in this study indicate that the statistical tests in this study accept or reject the complete spatial randomness hypothesis.

Based on the calculations obtained using the Anselin Local Moran's I index, the spatial landslide pattern can be classified into six types, including a statistically significant cluster of high values (only high–high cluster), a statistically significant cluster of low values (only low–low cluster), an outlier in which a high landslide ratio value was surrounded by low landslide ratio values (only high–low outlier), an outlier in which a low landslide ratio value was surrounded by high landslide ratio values (only low–high outlier), multiple types, and never significant.

6. The Original and Adjusted Definition of Spatiotemporal Hot Spot Patterns

The spatiotemporal hot spots were used in the study to observe the change, distribution, and hot spot patterns of landslide evolution using emerging hot spot analysis in ArcGIS Pro Software. The original definition of spatiotemporal hot spots is listed on the ESRI website, and the original definition was adjusted to be suitable for exploring and characterizing the pattern of landslide evolution in the study. The original and adjusted definitions of spatiotemporal hot spots are listed in Table 3 in the Supplementary Materials. The original definition of spatiotemporal hot spots is listed at https://pro.arcgis.com/en/pro-app/latest/tool-reference/space-time-pattern-mining/learn-moreemerging.htm#GUID-09587AFC-F5EC-4AEB-BE8F- 0E0A26AB9230

Table S3. The original and adjusted definition of spatiotemporal hot spot patterns.

Pattern	Original Definition	Adjusted Definition
No Pattern Detected	Does not fall into any of the hot or cold spot patterns defined below.	Does not fall into any of the hot or cold spot patterns defined below.
New Hot Spot	A location that is a statistically significant hot spot for the final time step and has never been a statistically significant hot spot before.	A landslide grid identified as a statistically significant hotspot since the first year of the research time period but was not previously identified as a statistically significant hotspot.
Consecutive Hot Spot	A location with a single uninterrupted run of at least two statistically significant hot spot bins in the final time-step intervals. The location has never been a statistically significant hot spot prior to the final hot spot run and less than 90 percent of all bins are statistically significant hot spots.	A landslide grid with a single uninterrupted run of statistically significant hotspot grids in the final year during the research time period. The landslide grid has never been a statistically significant hotspot before the final hotspot run.
Intensifying Hot Spot	A location that has been a statistically significant hot spot for 90 percent of the time-step intervals, including the final time step. In addition, the intensity of clustering of high counts in each time step is increasing overall and that increase is statistically significant.	A landslide grid that has been a statistically significant hotspot for 90% of the research time period. In addition, the clustering intensity of landslide for each year increased overall and that increase was statistically significant.
Persistent Hot Spot	A location that has been a statistically significant hot spot for 90 percent of the time-step intervals with no discernible trend in the intensity of clustering over time.	A landslide grid that has been a statistically significant hotspot for 90% of the research time period with no discernible trend indicating an increase in the clustering intensity of landslide over time.
Diminishing Hot Spot	A location that has been a statistically significant hot spot for 90 percent of the time-step intervals, including the final time step. In addition, the intensity of clustering in each time step is decreasing overall and that decrease is statistically significant.	A landslide grid that has been a statistically significant hotspot for 90% of the research time period, including the final year. In addition, the clustering intensity of landslide in each year is decreasing overall and that decrease is statistically significant.
Sporadic Hot Spot	A statistically significant hot spot for the final time-step interval with a history of also being an on-again and off-again hot spot. Less than 90 percent of the time-step intervals have been statistically significant hot spots and none of the time-step intervals have been statistically significant cold spots.	A landslide grid that is an on-again then off-again hotspot. Less than 90% of the research time period have been statistically significant hotspot and none of the time-step intervals have been statistically significant cold spot.
Oscillating Hot Spot	A statistically significant hot spot for the final time-step interval that has a history of also	A statistically significant hotspot or cold spot for the final year that has a history of also being

	being a statistically significant cold spot during a prior time step. Less than 90 percent of the time-step intervals have been statistically significant hot spots.	a statistically significant cold spot during a prior year. Less than 90% of the research time period have been statistically significant hotspot.
Historical Hot Spot	The most recent time period is not hot, but at least 90 percent of the time-step intervals have been statistically significant hot spots.	The most recent year is not hotspot, but at least 90% of the research time period have been statistically significant hotspot.
New Cold Spot	A location that is a statistically significant cold spot for the final time step and has never been a statistically significant cold spot before.	A landslide grid identified as a statistically significant cold spot since the first year of the research time period but was not previously identified as a statistically significant cold spot.
Consecutive Cold Spot	A location with a single uninterrupted run of at least two statistically significant cold spot bins in the final time-step intervals. The location has never been a statistically significant cold spot prior to the final cold spot run and less than 90 percent of all bins are statistically significant cold spots.	A landslide grid with a single uninterrupted run of statistically significant cold spot grids in the final year during the research time period. The landslide grid has never been a statistically significant cold spot before the final cold spot run.
Intensifying Cold Spot	A location that has been a statistically significant cold spot for 90 percent of the time-step intervals, including the final time step. In addition, the intensity of clustering of low counts in each time step is increasing overall and that increase is statistically significant.	A landslide grid that has been a statistically significant cold spot for 90% of the research time period. In addition, the clustering intensity of landslide for each year increased overall and that increase was statistically significant.
Persistent Cold Spot	A location that has been a statistically significant cold spot for 90 percent of the time-step intervals with no discernible trend in the intensity of clustering of counts over time.	A landslide grid that has been a statistically significant cold spot for 90% of the research time period with no discernible trend indicating a decrease in the clustering intensity of landslide over time.
Diminishing Cold Spot	A location that has been a statistically significant cold spot for 90 percent of the time-step intervals, including the final time step. In addition, the intensity of clustering of low counts in each time step is decreasing overall and that decrease is statistically significant.	A landslide grid that has been a statistically significant cold spot for 90% of the research time period, including the final year. In addition, the clustering intensity of landslide in each year is decreasing overall and that decrease is statistically significant.
Sporadic Cold Spot	A statistically significant cold spot for the final time-step interval with a history of also being an on-again and off-again cold spot. Less than 90 percent of the time-step intervals have been statistically significant cold spots and none of the time-step intervals have been statistically significant hot spots.	A landslide grid that is an on-again then off-again cold spot. Less than 90% of the research time period have been statistically significant cold spot and none of the time-step intervals have been statistically significant hotspot.
Oscillating Cold Spot	A statistically significant cold spot for the final time-step interval that has a history of also being a statistically significant hot spot during a prior time step. Less than 90 percent of the time-step intervals have been statistically significant cold spots.	A statistically significant cold spot for the final year that has a history of also being a statistically significant hotspot during a prior year. Less than 90% of the research time period have been statistically significant cold spot.
Historical Cold Spot	The most recent time period is not cold, but at least 90 percent of the time-step intervals have been statistically significant cold spots.	The most recent year is not cold spot, but at least 90% of the research time period have been statistically significant cold spot.

5. The Rainfall Seasonal Index values in Different Time Periods

The temporal distribution in 16 rainfall stations by using the rainfall seasonality from 2003 to 2017 is shown in Table 4.

Table S4. Temporal distribution of rainfall seasonality index in 16 rainfall stations in 2003–2017 in Taiwan.

No. of RS1	2003–208	2009–2017	2003–2017
1	0.63	0.61	0.62
2	0.39	0.35	0.36
3	0.49	0.45	0.47
4	0.66	0.66	0.65
5	0.55	0.59	0.56
6	0.81	0.81	0.78
7	0.69	0.61	0.64
8	0.41	0.49	0.45
9	0.76	0.73	0.73
10	0.85	0.82	0.84
11	0.66	0.52	0.56
12	0.75	0.73	0.70
13	0.92	0.67	0.78
14	1.02	0.92	0.94
15	0.87	0.70	0.74
16	0.73	0.63	0.64

References

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2. Liu, C.-C.; Chen, P.-L. Automatic extraction of ground control regions and orthorectification of formosat-2 imagery. *Opt. Express* **2009**, *17*, 7970–7984.
3. Liu, C.-C.; Shieh, C.-L.; Wu, C.-A.; Shieh, M.-L. Change detection of gravel mining on riverbeds from the multi-temporal and high-spatial-resolution formosat-2 imagery. *River Res. Appl*. **2009**, *25*, 1136–1152.
4. Liu, C.C.; Ko, M.H.; Wen, H.L.; Fu, K.L.; Chang, S.-T. Instability Index Derived from a Landslide Inventory for Watershed Stability Assessment and Mapping. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 145.