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# Global detection of rainfall triggered landslide clusters

Susanne A. Benz[1, 2], Philipp Blum[1]

[1] Karlsruhe Institute of Technology (KIT), Institute of Applied Geosciences (AGW), Karlsruhe, Germany

[2] University of California San Diego (UCSD), School of Global Policy and Strategy (GPS), La Jolla, CA, USA

*Correspondence to*: Philipp Blum (blum@kit.edu) and Susanne A. Benz (sabenz@ucsd.edu)

## Abstract

An increasing awareness of the cost of landslides on the global economy and of the associated loss of human life, has led to the development of various global landslide databases. However, these databases typically report landslide events instead of individual landslides, i.e. a group of landslides with a common trigger and reported by media, citizens and/or government officials as a single unit. The latter results in significant cataloging and reporting biases. To counteract this biases, this study aims to identify clusters of landslide events that were triggered by the same rainfall event. Here the developed algorithm is applied to the Global Landslide Catalog (GLC) maintained by NASA. The results show that more than 40 % of all landslide events are connected to at least one other event, and that 14 % of all studied landslide events are actually part of a landslide cluster consisting of at least 10 events. However, in a more regional analysis this number ranges from 30 % for the West Coast of North America to 3 % in the Himalaya Region. The cluster with most landslide events in a day is located in Rio de Janeiro, Brazil, with 108 events on 6$^{th}$ April 2010. In contrast, the longest running cluster was observed on the West Coast of North America with 132 events occurring in an area of over 120,000 km$^2$ during 24 days in December 2015. Our study intends to enhance our understanding of landslide clustering and thus will assist in the development of improved, internationally streamlined mitigation strategies for rainfall related landslide clusters.

**Keywords:** Landslide events; Database; Extreme weather; Rainfall induced; Early warning systems;

## 1. Introduction

The fatal and catastrophic nature of landslides has led to the development and maintenance of various global databases, such as the NASA Global Landslide Catalogue (GLC; e.g. Kirschbaum et al. 2015) and recently the Global Fatal Landslide Database (GFLD) by Froude & Petley (2018). Typically, these databases have a distinct focus. For example, the Global Landslide Catalogue (GLC) operated by NASA focuses on rainfall triggered landslides (Kirschbaum et al., 2010, 2015), whereas the Global Fatal Landslide Database records fatal landslides (Froude and Petley, 2018; Petley, 2012). Through these databases we are able to provide first estimates on the number of recorded fatalities, which were > 55,000 between 2004 and 2016 (Froude and Petley, 2018) and map near real-time risk for landslides almost on a global scale (Kirschbaum and Stanley, 2018). Still, while they play a key role in understanding the effects of landslides on our society, it is important to note that they are primarily based on news and government reports. These databases therefore do not count landslides, but landslide events, which contain either a single or a multitude of landslides within an area that are assumed to be triggered by the same event (Malamud et al., 2004). The exact number of slope failures in each event is often unknown and depends on the quality of the reporting. For some databases this number is included in a parameter of intensity or size of each event. Typically, for large databases however, this is merely qualitative and describes not only the number of individual landslides, but also an impact such as economic or human losses. This classification is commonly based on press releases and is therefore heavily biased on the news outlet reporting each event (e.g. Carrara et al., 2003).



Landslides triggered by catastrophic events, such as earthquakes or major storms, are often counted as one event containing thousands of individual landslides (Kirschbaum et al., 2015). In contrast, landslides caused by non-catastrophic events such as reasonable rainfall, are commonly counted as individual events, disregarding their shared trigger. Consequently, the overall extent of clustering in landslides is often unknown. But only if we better understand the extent of clustering between individual landslide events, will we be able to understand the patterns they occur in and have the chance to utilize these patterns to improve our forecast models (e.g. Martelloni et al., 2012).

Until now, few studies have focused on rainfall triggered landslide clusters and rather on temporal clusters over a long time period within a confined region (e.g. Samia et al., 2017; Witt et al., 2010). Biasutti et al. (2016) investigated the spatiotemporal clustering due to rainfall events for three selected urban areas of the US West Coast: Seattle, San Francisco and Los Angeles. Over the nine year study period, they found approximately 20 days within each city with multiple (up to eight) landslide events. Additionally, they could identify close to 40 landslide events that were followed by another event within the next week. However, with a focus on only selected study areas, they did not show the overall extend of these clusters.

The objective of this study is therefore to develop an algorithm, which is able to identify such clusters on a global scale. By applying the algorithm to the Global Landslide Catalog (GLC) the overall degree of clustering in the database is shown, and spatial patterns of clusters with at least 10 landslide events are described. Additionally, landslide events and rainfall patterns of the most intense and longest clusters are comprehensively discussed. In contrast to previous studies, such as by Biasutti et al. (2016), clusters here are not constricted by a maximum spatial extent, instead they are grouped by analyzing and comparing rainfall prior to the event at the event locations.

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## 2. Material and Method

### 2.1 Landslide Data

All landslide events within this study are part of the Global Landslide Catalog (GLC) operated by NASA and introduced in Kirschbaum et al. (2010, 2015). Data within the catalogue is based on online news articles that are found through search engine options such as Google Alerts. In the presented study, only events with a location accuracy ≤ 25 km are considered. As the rainfall data used is only available within ± 50° Latitude, landslide events outside of this range are not considered. Overall, a total of 9279 landslide events, ranging from 1988 to 2018 are analyzed (Fig. 1). However, only 45 of these events occurred before 2007, when the GLC was established.

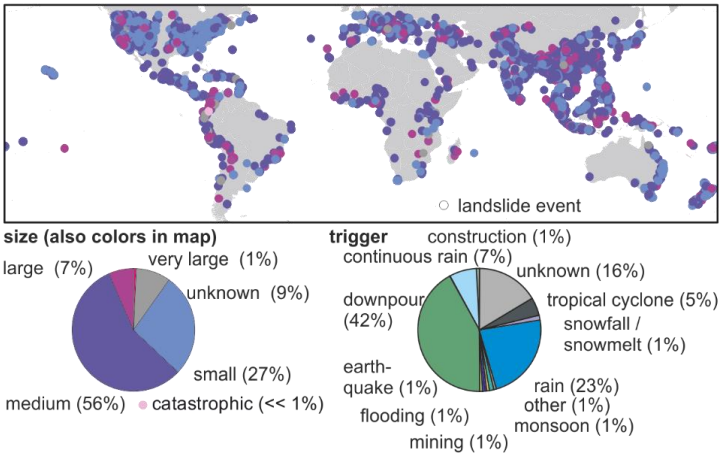


**Figure 1.** Map of all landslide events analyzed in this study and their size (also color in map) and apparent trigger. Overall a total of 9279 events were tested for clustering.

For each event, the GLC provides a landslide type, e.g. land- or mudslide, and a landslide trigger, e.g. rainfall, downpour, earthquakes or construction work. Detailed descriptions on these classifications can be found in Kirschbaum et al. (2010, 2015). Furthermore, within the GLC the intensity, impact, and number of landslides per event is expressed in a variable called “size”. While events classified as small in the database are only a single landslide, medium or larger landslide

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events may consist of multiple landslides within an unspecified range. About 64 % of the studied events are classified as medium or larger in size. However, a precise count of the number of landslides contained within these events does not exist in this database nor in any other of the global scale databases currently available. Within the GLC most of the small events that contain only a single landslide, are located within the United States (Fig. 1).

### 2.2 Rainfall Data

For the rainfall analysis, the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Climate Hazards Group, 2015) is used, which has a resolution of 0.05° × 0.05° and daily time steps. For each landslide event location, precipitation data were downloaded for 30 days preceding the event and up to two days after the event using Google Earth Engine (Gorelick et al., 2017). In order to compare rainfall during the event to overall rainfall at the location, the 95$^{th}$ percentile of precipitation excluding non-rainy days was determined for 10 years prior to the event. This comparison was also previously used by Kirschbaum et al (2015) to identify rainfall triggered landslide events. However, in their case, rainfall data from the Tropical Rainfall Measuring Mission (TRMM) was used for the time period 2000–2013 independent of the date of the landslide event. Due to the higher spatial resolution CHIRPS data was used here instead.

In addition to the 95$^{th}$ percentile of rainfall, the global rainfall threshold by Guzzetti et al. (2008) was also utilized to determine the likelihood of the individual landslide events being triggered by rainfall. In their study 2626 rainfall events that have resulted in shallow landslides and debris flows were analyzed in order to determine the following global rainfall intensity–duration threshold [http://rainfallthresholds.irpi.cnr.it]:

$$I = 2.2 \cdot D^{-0.44} \quad (1)$$


105 Here the threshold intensity (*I*) was determined for each 24 hours starting with a duration (*D*) of
106 12 hours. This results in an average precipitation of 0.73 mm/h for *D* = 12 h, 0.45 mm/h for *D* =
107 36 h, and 0.35 mm/h for *D* = 60 h. The rainfall threshold was then compared to the cumulative
108 mean precipitation of the rainfall event preceding each landslide event.

109 **2.3 Method**

110 The main objective of this study is to identify clusters of landslide events that occurred during, and
111 are likely triggered by the same rainfall event. To determine if two events, A and B, occurred during
112 the same rainfall event, two conditions have to be fulfilled: (I) A and B occurred within three days
113 of each other, and (II) spearman correlation between daily precipitation at A and at B is > 0.7 and
114 has a p-value < 0.05 for the 30 days preceding the later of the two events. Other landslide events
115 that fulfill these conditions with either A or B, are considered to be part of the cluster. A schematic
116 drawing of this algorithm is given in Fig. 2. The threshold value of three days maximum between
117 two events was used following Biasutti et al. (2016), who found it unlikely that landslide events
118 occurring more than three days apart, occurred during the same rainfall event. However, it is
119 important to note that their study was set in three metropolitan areas on the West Coast of the USA
120 and might not be applicable everywhere. The threshold value of the spearman correlation
121 coefficient was determined by testing the robustness of the identified clusters for different threshold
122 values between zero and one (Fig. S1). It was set to be 0.7 as from here on numbers of landslides
123 per cluster, duration of clusters, and area of clusters are stable for their mean and maximum values
124 (Fig. S1).

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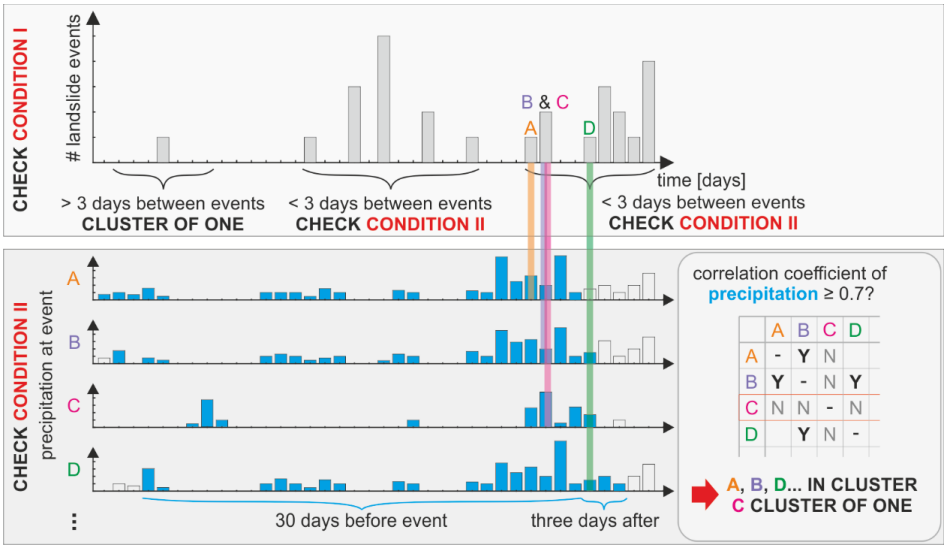


**Figure 2.** Schematic drawing of the algorithm used to identify, if two landslide events within the Global Landslide Catalog (GLC) occurred during the same rainfall event and hence belong to the same cluster. For condition II only events occurring within three days of each other are compared.

## 3. Results and Discussion

### 3.1 Clustering Characteristics

The presented algorithm divided the 9279 landslide events of the Global Landslide Catalog (GLC) into 6474 clusters of events connected through precipitation. However, 85 % of these clusters consist of only a single landslide event, containing in total 59 % of all recorded landslide events. This implies that a large number of landslide events are in fact isolated events with no association to other events. Nevertheless, 67 % of these ‘single landslide event’-clusters are categorized as medium or larger and might contain more than one landslide (in comparison 58 % of the landslide events in clusters ≥ one landslide event are categorized as medium or larger). Hence, the number of isolated landslides is likely to be significantly smaller than the number of isolated landslide events.

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In the Global Landslide Catalog (GLC) only 3 % of the analyzed landslide events are linked to triggers unrelated to rainfall such as construction, volcanos or earthquakes. This number is reduced to 1.5 % for landslides in a cluster of more than one event. Due to the low number of events in this category, future research is necessary to test and thoroughly validate these findings as well as to assess possible reasons and implications of this phenomenon. For now, we assume that this is mainly caused by biased reporting and cataloging of landslide events, where events linked to larger disasters such as earthquakes, might be reported as one large landslide event, whereas landslides linked to rainfall, might be individually reported. Similar observations were previously made by Kirschbaum et al. (2015) for events in the GLC that are linked to major storms. An example of this is the catastrophic magnitude 7.8 Gorkha earthquake in Nepal in 2015. While more than 25,000 landslides occurred during the earthquake and its aftershock sequence (e.g. Roback et al., 2018), they are only reported as 13 landslide events in the excerpt from the GLC analyzed here. In it, they are described as ranging in size from small to large and their trigger is given as “unknown”, “earthquake” and in one case “snowmelt”. Our algorithm sorts these events into eight clusters of up to three events.

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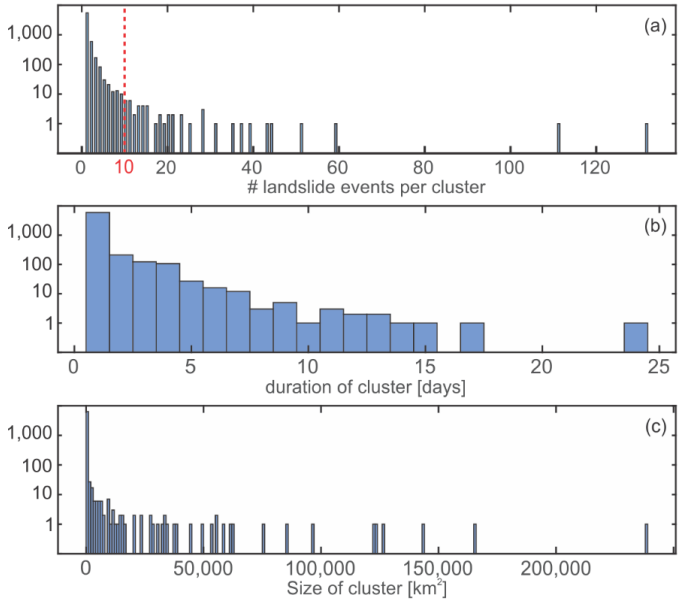


**Figure 3.** Histogram of the number of events per cluster, duration of clusters and area of the convex hull of each cluster. Clusters with only a single landslide event were appointed an area of zero. Within this study, all clusters with at least 10 landslide events were analyzed more closely.

Figure 3 provides histograms of the landslide events per cluster, duration of clusters and area covered by clusters (convex hull) in a logarithmic scale. As expected, for all three aspects frequency reduces drastically for larger numbers. In the following section all 50 clusters with at least 10 events (marked in red in Figure 3) are evaluated more closely.

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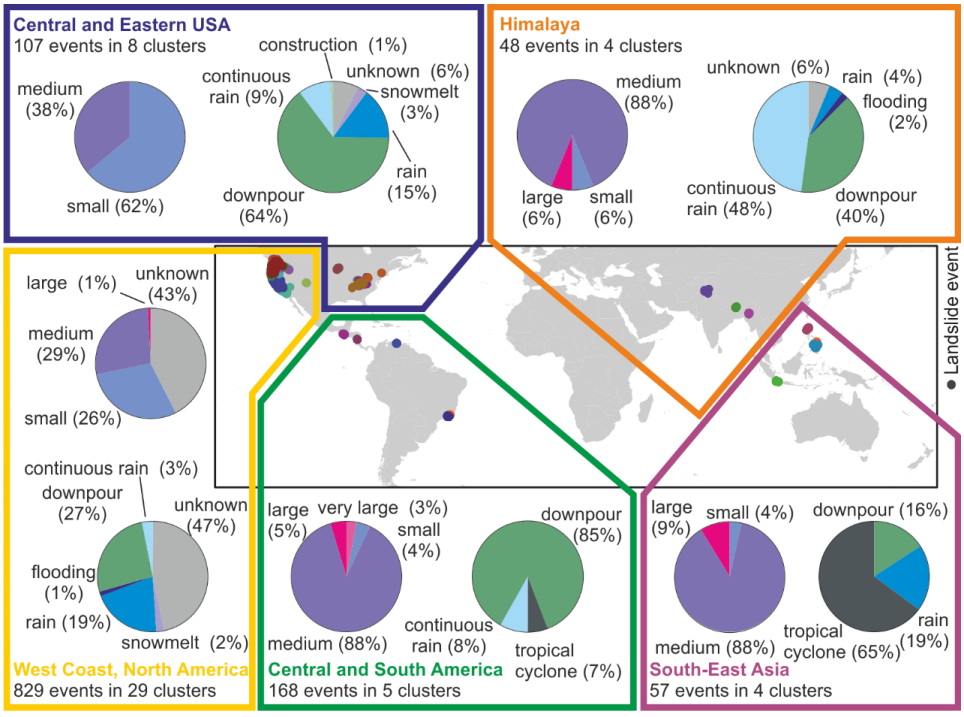


**Figure 4.** Location of all landslide events within clusters ≥ 10 events (different colors indicate different clusters). Overall, clusters in five distinct regions could be identified in the GLC (see Table S1 for more detail). Size and trigger (GLC categorization) of the associated landslide events are also shown.

## 3.2 Clusters with more than ten Landslide Events

### 3.2.1 Global Analysis

Table S1 gives more detail of the 50 clusters with at least 10 events. In total 13 % of all landslide events are associated with one of these clusters. As the database is most likely incomplete, the true number is expected to be higher. Overall the algorithm detects clusters in five distinct regions: (1) West Coast of North America, (2) Central and Eastern USA, (3) Central and Southern America, (4) Himalaya Region and (5) South-East Asia (Fig. 4). However, close to three quarters of all clusters ≥ 10 events are found within the USA mostly due to a bias in the GLC database (Kirschbaum et al., 2015) (Fig. 1). This is also shown in the size of recorded landslide events (Fig. 4).


176 In North America events are often classified as small in size, while clusters in the other regions
177 contain mainly medium events. This might be due to English speaking media, on which the GLC
178 is based, only picking up on large international events that consist of multiple landslides within an
179 area and smaller ones are under or not reported at all.

180 The median clusters with at least 10 events last six days, consist of 15 events, and span over an
181 area of 15,000 km² (Fig. 5). As expected, there is a positive correlation between cluster duration
182 and area (spearman correlation coefficient of 0.70, p-value: 0.001). However, this cannot be
183 observed for cluster duration and number of landslide events within the cluster (spearman
184 correlation coefficient of 0.44, p-value: 0.001). When comparing the different regions, clusters
185 located on the West Coast of North America are on average the longest and cover the largest area.
186 In contrast, events in South America are shortest and smallest, nevertheless they have the highest
187 number of events and clusters per day (Table 1).

188 On a global scale, no significant trend over time can be observed and clusters with ≥ 10 events
189 occur around the year (Fig. S2). Similarly, the total number of reported landslide shows no
190 significant increase in the GLC (Kirschbaum et al., 2015) as well as in other global databases such
191 as the Global Fatal Landslide Database (Froude and Petley, 2018). More regional observations
192 show seasonal variation and are described more closely in the following chapters. However, for
193 three out of the five regions, there are only five clusters or even less.

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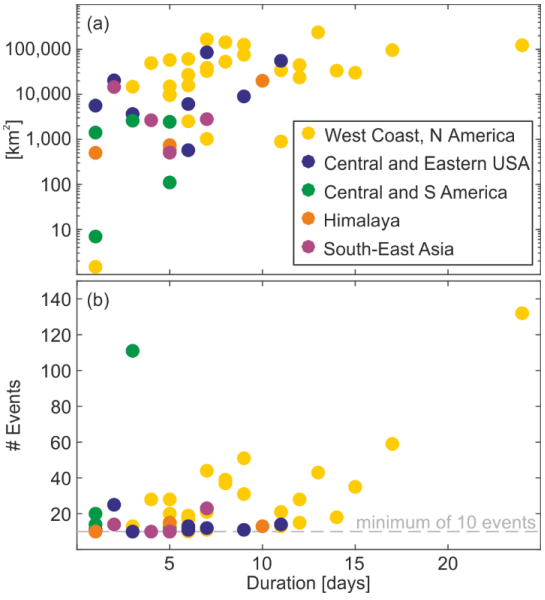


194

195 **Figure 5.** Link between the duration of the individual clusters ≥ 10 events and a) the covered area and b) the number
196 of landslide events per cluster. The color of the scatter plots indicates the region, in which each cluster occurred.

197 **Table 1.** Regional statistics for all landslide clusters (LC) with at least ten landslide events (LE).

| Region | # LC | # LE | LE per LC | Average duration of LCs | LEs per day | Average area of LCs [km²] | Percentage of LE in a LC ≥ 10 LE |
|---|---|---|---|---|---|---|---|
| West Coast, North America | 29 | 829 | 28.6 | 9 | 3.3 | 52,970 | 31 |
| Central and Eastern USA | 8 | 107 | 13.4 | 6 | 2.4 | 23,357 | 12 |
| South and Central America | 5 | 168 | 33.6 | 3 | 11.2 | 1,320 | 18 |
| Himalaya | 4 | 48 | 12.0 | 5 | 2.3 | 5,476 | 3 |
| South-East Asia | 4 | 57 | 14.3 | 5 | 3.2 | 5,143 | 4 |

198

199 ### 3.2.2 West Coast, North America

200 Landslides in the west of North America have been intensively investigated, mainly in the form of
201 case studies that discuss landslides along the Pacific coast in the states of California (Collins and
202 Sitar, 2008; Wieczorek, 1988), Oregon (Benda, 1990; Miller and Burnett, 2008) and Washington


(LaHusen et al., 2016; Perkins et al., 2017). This region is also one of the few, where the clustering of rainfall triggered landslide events was previously investigated, showing qualitatively that there are many instances in which landslides occur on consecutive days (Biasutti et al., 2016).

About 31 % of all landslide events recorded in this area belong to a cluster of at least ten events. This is the highest number compared to the other regions of the world (Table 1). However, this effect might be amplified by the high number of reported landslides. The large number of events and clusters is mainly due to geologic, topographic, climatic conditions and construction practices. For example in Oregon, steep slopes and heavy rainfalls are as well as poor construction practices result in high economic losses (Wang et al., 2002). Burns et al. (2017) estimated an average annual loss of $15.4 million due to landslides in Oregon alone. In years with heavy storms such as 1996, this can accumulate to more than $100 million (Wang et al., 2002).

The observed clusters in this area are among the longest and have the largest areas of all regions (Table 1). While the size of landslide events (as given by the GLC) in the west of North America are small compared to most other regions, there is also a considerable amount of events, where the size is unknown (43 %, Fig. 4). While about half of the landslide events within clusters ≥ 10 events are classified as “trigger unknown” (47 %), landslide events with a known cause are mainly triggered by downpour (27 %) or rain (19 %) (Fig. 4). However, when looking at satellite based rainfall data preceding the clusters, rainfall cannot always be identified as a trigger (Fig. S3). While it generally exceeds the global rainfall threshold (Guzzetti et al., 2008), the 95$^{th}$ percentile of precipitation on rainy days is not reached for the majority of the clusters. Although, several studies linked landslides within California to earthquakes (e.g. Harp and Jibson, 1996; Keefer, 2000), they occurred before 2007 and are not registered in the GLC.


225 While there appears to be no significant change in the number of clusters over time (Fig. S2), most
226 clusters occur during the rainy season (November to March), when most landslide events occur.
227 Within the west of North America this time period is therefore often referred to as the "landslide
228 season" (e.g. Mirus et al., 2018). Only one cluster in this region appears in June (Cluster ID 21,
229 Table S1). However, the center of this cluster is located more inland (in San Miguel County,
230 Colorado) and is also the shortest cluster (only one day) within the region as well as the most local
231 of all clusters in this study, covering only 1 $km^2$. While this cluster is triggered by downpour
232 according to the GLC, this is not apparent from satellite derived precipitation (Fig. S3). The small
233 size of the cluster might be the reason, why low-resolution satellite derived precipitation does not
234 record any anomalies here.

235 **3.2.3 Central and Eastern USA**

236 While most of the clusters with ≥ 10 landslides events of this region, are located in the Appalachian
237 Plateau (Ohio, West Virginia and Kentucky), one cluster can be found in Minnesota (ID 34 in Table
238 S1 and Fig. S4). While it is considerably smaller (580 $km^2$ compared to > 9,000 $km^2$), it is
239 comparable to the Appalachians cluster in its number of landslide events and duration. The
240 Appalachian Plateau is well known for its landslides and the annual direct cost in Kentucky exceeds
241 $10 million (Crawford and Bryson, 2017).

242 Like the landslide clusters observed in the west of North America, clusters here consist mainly of
243 small landslides, which is most likely linked to the news alerts on which the GLC is based.
244 Checking sources in the GLC, they are mainly reported within smaller, more local news outlets
245 compared to landslide events outside of the US. To our knowledge the individual events grouped
246 by our algorithm into clusters have never been linked before. Clusters in this region occur
247 predominantly in spring (February to June), when rainfall is highest, slightly later than events on


248 the West Coast (Fig. S2). According to GLC they are predominantly triggered by downpours (64 %,
249 Fig. 4). However, extreme rainfall is not always visible in satellite derived precipitation (Fig. S4).
250 For most clusters, it is below the 95$^{th}$ percentile, but above the global threshold. It is worth noting
251 than one cluster located in West Virginia (Cluster ID 35) shows no rainfall on the satellite before
252 day three of the cluster. Following the GLC, early landslide events within this cluster are linked to
253 snowmelt.

254 **3.2.4 Central and South America**

255 In contrast to the clusters in North America, more than 95 % of landslide events within clusters of
256 this region are medium in size or larger and might consists of several landslides themselves (Fig.
257 4). Thus, the number of landslides per cluster and per day is likely to be significantly higher than
258 the number of events per cluster and per day. Still, clusters in this area are on average only two and
259 a half days long, covering an area of slightly over 1,500 km² and they are the smallest and shortest
260 of all regions (Fig. 5, Table 1). It is important to note that this region covers the largest area reaching
261 from Rio de Janeiro in Brazil to Guatemala in Central America. From the few clusters we could
262 identify, it appears that there are dissimilarities between the clusters in Central America and South
263 America. The two clusters in Nicaragua (ID 42) and Guatemala (ID 39) are triggered by continuous
264 rain and a tropical cyclone, respectively. In contrast, all events located in South America (IDs 38,
265 40, and 41) are all triggered by downpour (Table S1 and Fig. S5).

266 **3.2.5 Himalaya**

267 Like in South America, most landslide events (94 %) associated with clusters with ≥ 10 events in
268 the Himalaya region are categorized as medium and larger. Thus, the number of landslides per
269 cluster is again expected to be significantly higher than the number of landslide events per cluster.
270 However, there may be differences between regions. Event ID 44, located in India and Pakistan


271 around Jammu and Kashmir, is classified as medium to small, much longer (10 days) and covers
272 an area more than 10 times larger than the other clusters. All of them are classified as medium or
273 large and are located in the East of India with some events in Nepal (Table S1). In both regions,
274 clusters are triggered by continuous rain or downpour. For all clusters satellite based rainfall data
275 exceeds the global threshold, and in most cases the 95th percentile of rainfall on rainy days (Fig.
276 S6). It is important to note that while earthquake triggered landslides are common in the region
277 (e.g. Parkash, 2013; Roback et al., 2018), the presented algorithm is by design only able to pick up
278 clusters that are linked by rainfall.

279 **3.2.6 South-East Asia**

280 As only four clusters are identified in this region, a detailed analysis is impossible. Again, 96 % of
281 the events associated are categorized as medium or larger and the main triggers are tropical
282 cyclones (Cluster IDs 47 and 48), downpour (Cluster ID 49), and rain (ID 50) (Table S1). Here,
283 satellite based rainfall data before clusters is both above the global rainfall threshold and in most
284 cases above the 95$^{th}$ percentile (Fig. S7). While only one of the four clusters (ID 50) is recorded
285 outside of the Philippines (in Indonesia), there is no apparent difference between both countries
286 (Table 1).

287 **3.3 Most Intense Cluster**

288 The cluster with the most events in one day, i.e. most intense cluster, happened in Rio de Janeiro,
289 Brazil, as well as neighboring cities Niteroi and Sao Goncalo in 2010. In an area of approximately
290 2,800 km$^2$, 111 landslide events were recorded within only three days, however predominantly on
291 6$^{th}$ April 2010 (Table S1, ID 38). This is almost four times as many landslide events in a single day
292 than the second most intense clusters (IDs 1 and 3) located in Washington and Oregon, USA. Both
293 recorded 29 events in one day.

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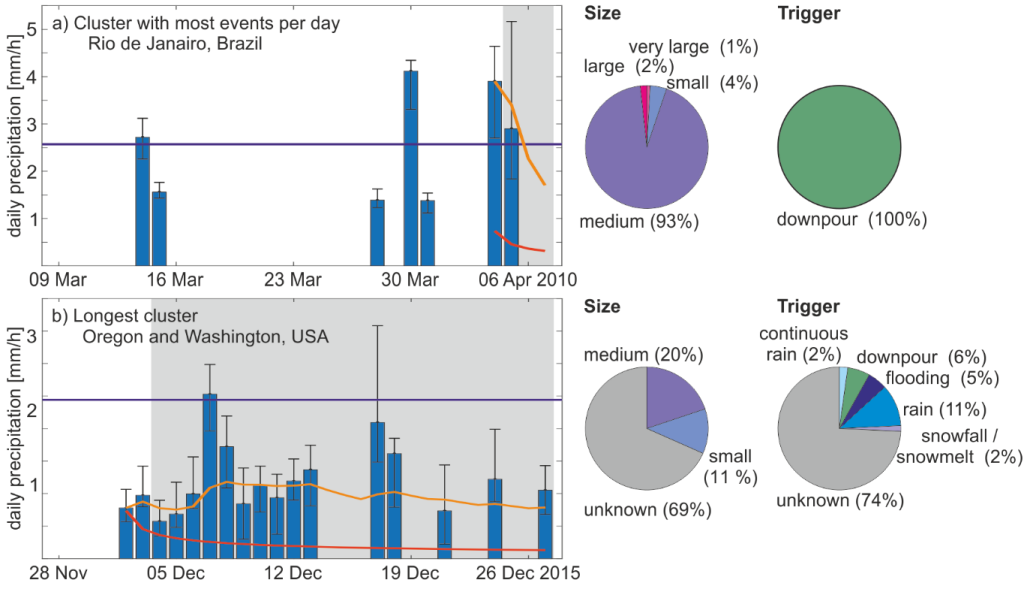


**Figure 6.** Daily precipitation for 30 days preceding the last landslide event of the cluster with the size of the associated landslide events and their trigger according to the GLC. Shown is the median precipitation for all landslide locations with the inner quartiles as an error bar. The 95$^{th}$ percentile of daily rainfall (rainy days only) in the ten years preceding the event is given in blue, in red the global rainfall threshold ID (Guzzetti et al., 2008) and in orange the cumulative mean for the rainfall event preceding the cluster. a) Cluster with the most events per day (ID 43), and b) longest running cluster (ID 22).

Most of the 111 events associated with the cluster in Rio de Janeiro were recorded as medium in size, all of which were triggered by downpour (Fig. 6a). This is confirmed by satellite derived precipitation. Heavy rainfalls (Figs. 6a, 7) occurred on the 4$^{th}$ and 5$^{th}$ of April of up to 210 mm per day. In comparison, the 95$^{th}$ percentile in the 10 years preceding this cluster is on average only 62 mm per day (rainfall for each individual location shown in Fig. S8). While the rainfall covered a large area, landslide events were primarily reported for steep slopes just outside the densely populated city center. Due to its location close to, and inside the urban area of Rio de Janeiro, the cluster caused approximately 200 fatalities according to CNN news reports (http://www.cnn.com/2010/WORLD/americas/04/12/brazil.flooding.mudslides/).

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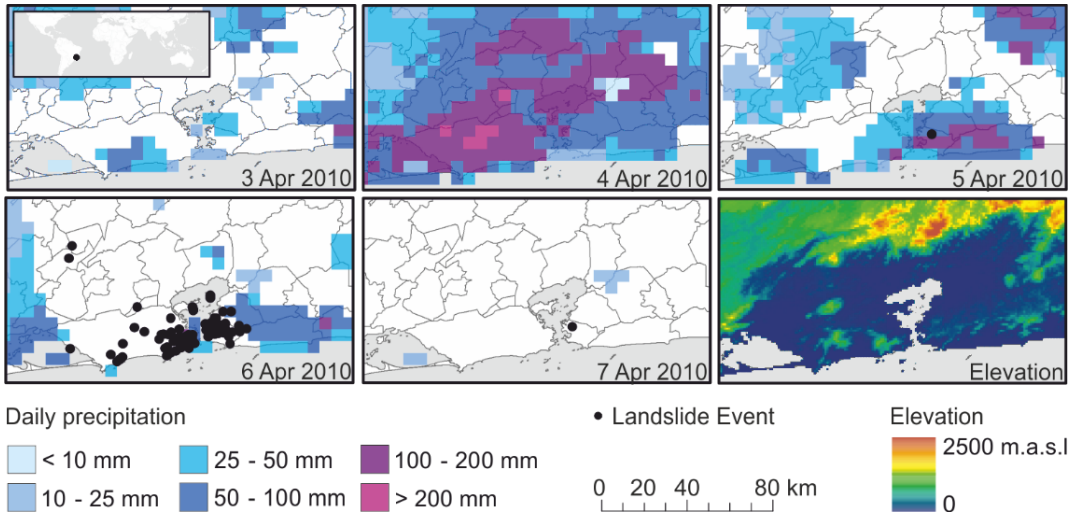
310 The location in the city might also be the reason for the large number of events being reported, as
311 we can expect more individual landslides being reported here compared to the countryside.

312 While studies not based on English speaking news alerts report a large number of landslides within
313 and around Rio de Janeiro (Calvello et al., 2015; Sandholz et al., 2018), only nine additional
314 landslide events inside the area of this cluster were reported in the GLC between 2009 and 2018.
315 Additionally, just northwest of the cluster another cluster occurred in January 2011 (ID 41 in Table
316 S1, Fig. S5). Although, this cluster only counts 20 individual landslide events within the GLC, it
317 is being reported as thousands individual landslides (Coelho Netto et al., 2013).




318

319 **Figure 7.** Location of the events in the cluster with the most events per day located in Rio de Janeiro, Brazil. Also
320 shown are daily precipitation and elevation. Elevation data is taken from the US Geological Survey (GTOPO30).

321 **3.4 Longest Cluster**

322 The longest running cluster identified in this study occurred in Oregon and Washington, USA from
323 4th to 27th December 2015 for a total of 24 days with 132 landslide events (Cluster ID 18, Table
324 S1). The second longest cluster lasted 17 days over January and February in 2012 and was also



325 located in Oregon and Washington, USA (Cluster ID 7). Overall, most events within the longest
326 cluster are unknown in size (69 %) and trigger (74 %) (Fig. 6b). However, inspecting satellite based
327 rainfall data, continuous rainfall appears to be the main trigger (Fig. 6b, Fig. 8 and Fig. S9 for
328 rainfall at the individual event locations). While daily rainfall is mainly below the 95$^{th}$ percentile,
329 cumulative mean rainfall is continuously above the global rainfall threshold. Although, heavy
330 rainfall is common in this area during winter times, for this cluster it lasted longer than usual and
331 was followed by shorter rain events in short successions (Fig. 8). Thus, the series of landslides did
332 not halt resulting in the longest cluster in the GLC. Following the information on sources within
333 the GLC, it appears that local media reported about the individual landslide events, but did not
334 detect on the extreme length of the continuous series of landslide events at this point in time (e.g.
335 https://kval.com/news/local/landslide-blocks-i-5-in-sw-washington;
336 https://q13fox.com/2015/12/09/landslide-above-puget-sound-damages-several-homes-at-least-
337 one-vehicle/). As landslide events are such a common occurrence in this region, and due to the
338 large area covered by this cluster, there is currently little to no emphasis on the longevity of this
339 specific series of landslide events in media and scientific studies.

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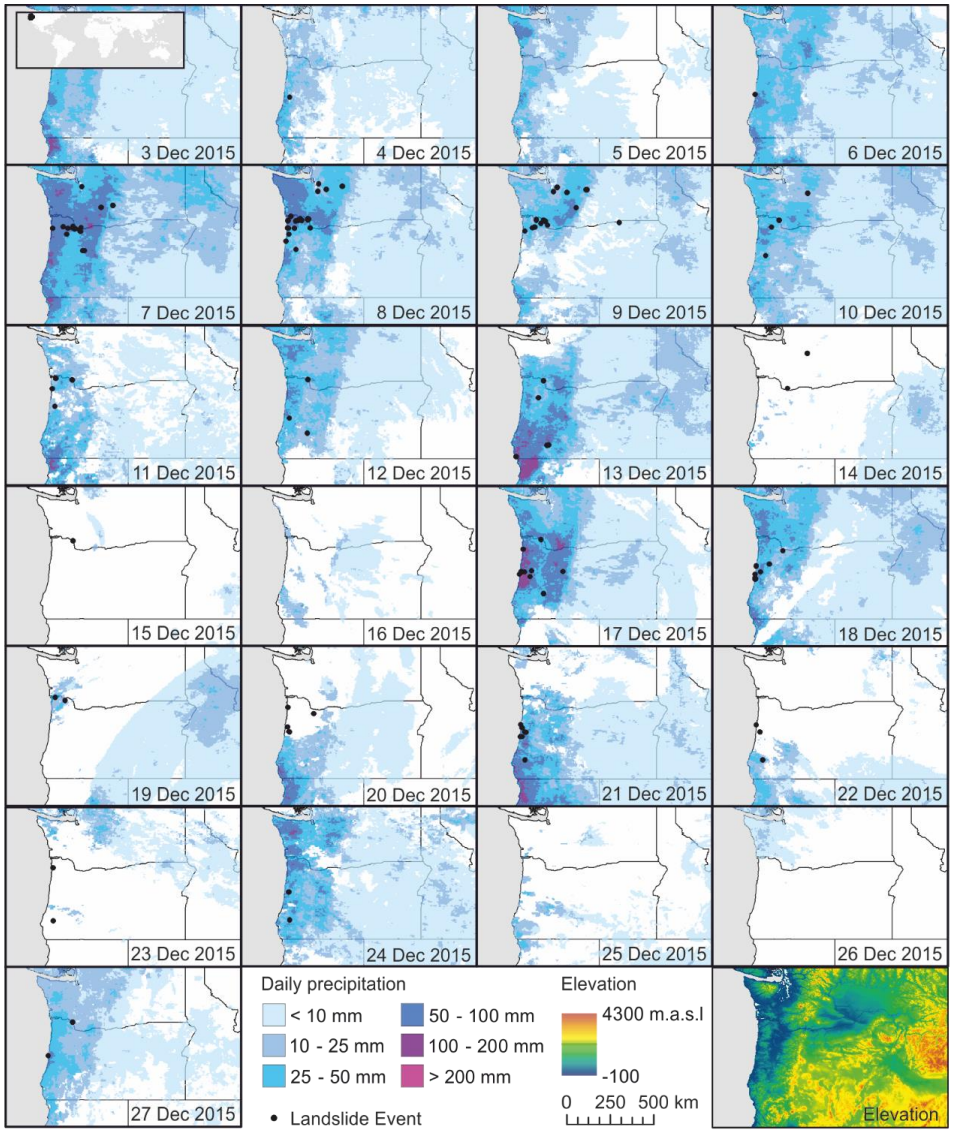


**Figure 8.** Location and time series of the longest cluster, located mainly in Oregon, USA. Also shown are daily rainfall and elevation. Elevation data is available from the US Geological Survey (GTOPO30).

## 4. Conclusion

In this study an algorithm is presented that detects clusters of landslide events that occur during, and are likely triggered by the same rainfall events. Here this algorithm is applied to the Global


346 Landslide Catalog (GLC), where it detects that more than 40 % of all recorded events can be linked
347 to at least one other event. The global analysis shows that 14 % of all landslide events are part of a
348 cluster ≥ 10 events. However, this percentage varies dramatically by the region, ranging from 30 %
349 on the West Coast of North America to 3 % in the Himalayas. Part of this is caused by sampling
350 and reporting bias. As the GLC is based on English speaking media, events in the USA are reported
351 and cataloged in much greater detail than events abroad. Nevertheless, within the GLC we could
352 detect clusters ≥ 10 landslide events in five distinct regions: (1) West Coast of North America, (2)
353 Central and Eastern USA, (3) Central and Southern America, (4) Himalaya Region, and (5) South-
354 East Asia. In South America, the studied clusters are the shortest, but contain the most events per
355 day. However, this is mainly due to a cluster in Rio de Janeiro, where 108 of events were recorded
356 on 6$^{th}$ April 2010. As most of these events are classified as medium or larger, the absolute number
357 of landslides is expected to be significantly higher. In contrast, the longest and largest clusters are
358 observed on the West Coast of North America. On average clusters here last nine days and cover
359 an area of more than 50,000 km$^2$. The steep slopes and continuous rainfalls present in the area
360 combined with the above average reporting of landslide events, makes a more detailed analysis of
361 rainfall related landslide clusters possible. The longest of all detected clusters ≥ 10 landslide events
362 is also located in this region: In December 2015, 132 landslide events were recorded over a time
363 period of 24 days spanning more than 120 thousand km$^2$, which were all triggered by the same
364 rainfall event. Detection of large scale clusters such as this one can not only help to improve our
365 understanding of the link between individual events, but also be used in our mitigation strategies.
366 Only once we improve our understanding of the relation between individual landslide events, we
367 will be able to predict their behavior and forecast their economic losses and fatalities. While our
368 study does not replace case specific and small scale studies, as well as the identification of threshold
369 values, it can provide an improved understanding for managing landslide mitigations on a larger


370 scale. Within the area covered by individual clusters the same mitigation strategies, including early
371 warning systems (EWS) based on weather forecast simulations, can be developed and validated.
372 For future research we recommend to use the presented algorithm not only for the correlation with
373 precipitation data, but also to include the geometry of atmospheric rivers during cluster detection.
374 Finally, the algorithm could be applied to more regional and other global landslide databases
375 thereby improving our understanding on the spatial and temporal occurrence of landslide clusters.

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