Mass wasting triggered by the 2008 Wenchuan earthquake is greater than orogenic growth

Landslide mapping methods. In order to rapidly map slope failures over the large rupture zone, semi-automated landslide detection techniques were developed using a combined spectral and topographic model. A full description of these techniques is provided in Parker\textsuperscript{51}.

Panchromatic classification algorithm (EO-1 imagery)

In the 10 m panchromatic EO-1 imagery acquired for the investigation (Supplementary Table 1), landslide scars appear as bright regions where darker vegetation cover has been removed, exposing soil and rock. The result is an image with sharp contrast between the high pixel (Digital Number or DN) values of landslide-affected areas and much lower values on adjacent hillslopes. By applying an appropriate pixel intensity threshold, based on the best visual classification result for each image, landslide and non-landslide areas were extracted to a binary classification. However, additional regions with high DN values include urban areas, roads and high sediment loaded rivers. In order to remove these regions from the classification, areas with topographic gradients of less than 20° were eliminated using 90 m SRTM DEM data. This optimal value of the gradient mask was estimated through trial and error by comparing landslide areas derived from mask values ranging from 10-40° (in 1° increments) with visually-identifiable landslide areas in the original imagery.

Multispectral classification algorithm (SPOT 5 imagery)

In the 5 and 10 m multispectral SPOT 5 imagery (Supplementary Table 1), landslide scars exhibit a high level of spectral contrast with adjacent vegetated slopes. We followed Borghuis et al.\textsuperscript{52} and applied maximum likelihood-based unsupervised classification to separate landslide and non-landslide areas. The unsupervised classification was used to separate the images into spectral classes, after which landslide and non-landslide classes were selected based on the best visual result for each image. Again a 20° gradient mask (optimised as above) was applied to eliminate
developed areas and rivers with spectral signatures similar to landslide scars. Supplementary Figure 1 shows a comparison between the results of manual and unsupervised classification for an individual landslide.

**Object-oriented filtering**

Classification masks for all coverage areas were combined and converted to landslide polygons. In some areas, additional false positives were produced by sections of road on steep slopes, arable fields, or along rough edges produced by the coarse slope mask resolution. A series of object-oriented filters were applied to remove these errors, based on the size, shape and orientation properties of classified features. The main filter used in this process considered the direction of alignment of landslide polygons relative to the topography. Those polygons with their long axes aligned in the down-slope direction were preserved, while those with more than a 40° angular difference between their long axes and the hillslope aspect were removed. Groups of adjacent pixels with total areas of less than 300 m² (three pixels on the 10 m EO-1 and SPOT 5 images, 12 pixels on the 5 m SPOT 5 images) that were originally classified as landslides were also removed at this stage. Finally, we removed polygons with circularity ratios of > 0.7, as these were dominantly caused by cultivated fields, and those with length-to-width ratios of > 7, as these were dominated by roads and stream channels. Optimum values for all of these filters were chosen based on trial and error comparison with visually-identifiable landslide areas on the original imagery.

Finally the full map was inspected visually, and manual corrections were made where necessary. At this stage, pre-earthquake Landsat 7 ETM+ and Landsat 5 imagery was also used for comparison and to allow for the removal of landslides present before the earthquake. The basis for using this method is that newly-formed landslides produce clear scars within vegetated areas as visible on the Landsat imagery. Regions above 3500 m elevation have very little vegetation cover, and thus newly formed landslide scars could not be identified. These regions, along with areas of cloud cover, were therefore removed from the final classification coverage (Fig. 1).
The landslide map was checked against manually-mapped landslides in three 6 km x 6 km validation sample areas distributed across the Longmen Shan. The automated mapping techniques produced a net underestimation of landslide areas, relative to manually mapped results, of between 6.2 and 22.7% across these three areas. This underestimation was produced through the combination of errors of commission (areas falsely classified as landslides) and errors of omission (areas of landslides not classified as such). Areas commissioned by automated but not manual techniques equated to between 3.2 and 5.6% of the total sample area, while areas omitted by automated mapping equated to between 7.4 and 12.5% of the total manually mapped area. These errors result in a net areal automated-manual overlap of between 58.7 and 66.2%, similar to the values achieved through application of the same method by Borghuis et al.\textsuperscript{52} of between 53 and 66%. As a percentage of the total sample area mapped, these results indicate an overall landslide density underestimation of between 1.8 and 9.3%.

Because landslide mapping relied on a threshold in either intensity (panchromatic imagery) or spectral signature (multispectral imagery), the image resolution places a first-order constraint on the resulting area of individual landslides. Whether a given image pixel is included in a landslide or not depends on its DN value(s); thus delineation of landslide boundaries at a sub-pixel level is not possible. This limitation is shared by other methods, such as mapping on aerial photographs.

**Landslide pattern and summary statistics.** In total we derived 73,367 landslide features across the 13,800 km\(^2\) mapped area. The probability density distribution of landslide areas derived from our mapping technique is very similar to that reported from other large earthquake-triggered landslide data sets (e.g., the 1994 Northridge\textsuperscript{53} and 1999 Chi-Chi\textsuperscript{54-56} earthquakes). Supplementary Figure 2 shows that our data can be described by similar inverse-gamma or double-Pareto distribution functions\textsuperscript{57}.

Our total number of landslides is somewhat higher than the total of 56,847 landslides mapped across an area of 41,750 km\(^2\) by Dai et al.\textsuperscript{58} using manual mapping techniques. Exact comparison of the two data sets is difficult, but we note that our overall landslide density, given by \(\frac{\sum A_{ls}}{A_{map}}\),
where $A_{\text{map}}$ is the total mapped area, is 4.1%, compared with 1.94% found by Dai et al.\textsuperscript{58}. This is expected given that our mapped area is focused more closely on areas near the surface rupture (Fig. 1) and does not include areas far from the rupture with low rates of landslide occurrence\textsuperscript{57}.

**Landslide volumes.** In areas of high landslide density, coalescing landslide features are difficult or impossible to identify and delineate as individual failures, either manually or using an automated or semi-automated mapping technique. In these regions, some underestimation of the total number of landslides and some overestimation of the area of individual failures may be expected. These uncertainties have important implications for volume estimates, due to the non-linear relationship between area and volume\textsuperscript{59}. The estimated volume for a single feature encompassing multiple landslides will be greater than the sum of estimated volumes calculated for those same landslides when mapped individually. The calculated landslide volumes for coalescing landslides will thus be maxima. This consideration applies to not only this investigation but all studies seeking to scale landslide volumes from landslide area\textsuperscript{58,59}, particularly in areas of high landslide density. Without independent landslide area-frequency data, it is difficult to assess the effect of this area overestimation on our results. However, we used the approximate cumulative number-area relationship of Dai et al.\textsuperscript{58} to derive a first-order estimate of landslide volume, reasoning that their manual mapping technique may have a different (although unknown) sensitivity to area overestimation than our semi-automated approach. The total landslide volumes that we derive agree with those based on our data (Table 1) to within 15-20%, suggesting that the mismatch between landslide and tectonic volumes that we document is not due to artefacts in our mapping technique. In addition, the probability density distribution of landslide area derived from our mapping (Supplementary Figure 2) does not suggest a large-scale bias in our data set toward large individual landslide areas (and thus overestimates of landslide volume) relative to other earthquake events\textsuperscript{57}, as might be expected if our semi-automated technique were particularly susceptible to this issue.

**Supplementary References**


**Supplementary Figure Captions**

S1. **Comparison of manual and automated landslide mapping results.** Background image is a SPOT 5 multispectral image (5 m resolution). a, outline of the Jingjiashan/Xinbei Middle School landslide, Beichuan town, derived from manual mapping. b, result of unsupervised classification of the SPOT 5 image before application of a gradient mask and object-oriented filters. Black areas are classified as landslides. c, result of unsupervised classification after application of a 20°
gradient mask. Black areas are classified as landslides. Object-oriented filters have not yet been applied to the classification results.

S2. Landslide probability density as a function of landslide area. Grey circles show landslides from this study, black squares show landslides triggered by the 1994 Northridge earthquake\textsuperscript{33}, USA, and white circles show landslides triggered by the 1999 Chi-Chi earthquake\textsuperscript{54-56}, Taiwan.

Supplementary Table 1. Satellite imagery used in landslide mapping.

<table>
<thead>
<tr>
<th>Scene ID</th>
<th>Acquisition date</th>
<th>Sensor</th>
<th>Spectral bands*</th>
<th>Resolution (m)</th>
<th>Path</th>
<th>Row</th>
</tr>
</thead>
<tbody>
<tr>
<td>52612860806040402292U</td>
<td>04/06/2008</td>
<td>SPOT 5</td>
<td>G R NIR</td>
<td>5</td>
<td>261</td>
<td>286</td>
</tr>
<tr>
<td>52592870812150328292J</td>
<td>15/12/2008</td>
<td>SPOT 5</td>
<td>G R NIR MIR</td>
<td>10</td>
<td>259</td>
<td>287</td>
</tr>
<tr>
<td>52602870810130341052J</td>
<td>13/10/2008</td>
<td>SPOT 5</td>
<td>G R NIR MIR</td>
<td>10</td>
<td>260</td>
<td>287</td>
</tr>
<tr>
<td>52582880901150333322J</td>
<td>15/01/2009</td>
<td>SPOT 5</td>
<td>G R NIR MIR</td>
<td>10</td>
<td>258</td>
<td>288</td>
</tr>
<tr>
<td>EO1A1300382008189110K0PF101</td>
<td>07/07/2008</td>
<td>EO-1 ALI</td>
<td>Pan</td>
<td>10</td>
<td>131</td>
<td>38</td>
</tr>
</tbody>
</table>

* G, green (0.5-0.59 \(\mu\)m); R, red (0.61-0.68 \(\mu\)m); NIR, near infra-red (0.78-0.89 \(\mu\)m); MIR, mid infra-red (1.58-1.75 \(\mu\)m); Pan, panchromatic (0.48-0.71 \(\mu\)m).
Supplementary Figure 1. Comparison of manual and automated landslide mapping results.
Background image is a SPOT 5 multispectral image (5 m resolution). a, outline of the Jingjiashan/Xinbei Middle School landslide, Beichuan town, derived from manual mapping. b, result of unsupervised classification of the SPOT 5 image before application of a gradient mask and object-oriented filters. Black areas are classified as landslides. c, result of unsupervised classification after application of a 20° gradient mask. Black areas are classified as landslides. Object-oriented filters have not yet been applied to the classification results.
Supplementary Figure 2. Landslide probability density as a function of landslide area. Grey circles show landslides from this study, black squares show landslides triggered by the 1994 Northridge earthquake, USA, and white circles show landslides triggered by the 1999 Chi-Chi earthquake, Taiwan.