



Long-term erosion of the Nepal Himalayas by bedrock landsliding: the role of monsoons, earthquakes and giant landslides

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In active mountain belts with steep terrain bedrock landsliding is a major erosional agent. In the Himalayas, landsliding is driven by annual hydro-meteorological forcing due to the summer monsoon and by rarer, exceptional events, such as earthquakes. Independent methods yield erosion rate estimates that appear to increase with sampling time, suggesting that rare, high magnitude erosion events dominate the erosional budget. Nevertheless, until now, neither the contribution of monsoon and earthquakes to landslide erosion, nor the proportion of erosion due to rare, giant landslides have been quantified in the Himalayas. We address these challenges by combining and analyzing earthquake and monsoon induced landslide inventories across different timescales. With time-series of 5 m satellite images over four main valleys in Central Nepal, we comprehensively mapped landslides caused by the monsoon from 2010 to 2018. We found no clear correlation between monsoon properties and landsliding, and a similar mean landsliding rate for all valleys, except in 2015, where the valleys affected by the earthquake featured ~ 5 -8 times more landsliding than the pre-earthquake mean rate. The long-term size-frequency distribution of monsoon induced landslides (MIL) was derived from these inventories and from an inventory of landslides larger than ~ 0.1 km² that occurred between 1972 and 2014. Using a published landslide inventory for the Gorkha 2015 earthquake, we derive the size-frequency distribution for earthquake-induced landslides (EQIL). These two distributions are dominated by infrequent, large and giant landslides, but underpredict an estimated Holocene frequency of giant landslides (>1 km³) which we derived from a literature compilation. This discrepancy can be resolved when modelling the effect of a full distribution of earthquake of variable magnitude and considering that shallower earthquake may cause larger landslides. In this case, EQIL and MIL contribute about equally to a total long-term erosion of $\sim 2 \pm 0.75$ mm.yr⁻¹ in agreement with most thermochronological data. Independently of the specific total and relative erosion rates, the heavy-tailed size-frequency distribution from MIL and EQIL and the very large maximal landslide size in the Himalayas indicate that mean landslide erosion rates increase with sampling time, as has been observed for independent erosion estimates. Further, we find that the sampling time scale required for adequately capturing the frequency of the largest landslides, which is necessary for deriving long-term mean erosion rates, is often much longer than the averaging time of cosmogenic ¹⁰Be methods. This observation presents a strong caveat when interpreting spatial or temporal variability of erosion rates from this method. Thus, in areas where very large, rare landslide contributes heavily to long-term erosion (as the Himalayas), we recommend ¹⁰Be sample in catchments with source areas $>10,000$ km², to reduce the method mean bias below $\sim 20\%$ of the long-term erosion.