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Landslides, hurricanes, and sediment sourcing impact basin-scale erosion estimates in Luquillo, Puerto Rico

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ABSTRACT

Accurately inferring erosion rates from cosmogenic isotope concentrations in river sand assumes temporally steady concentrations; few studies test this assumption. Following Hurricane María in Puerto Rico, we quantified temporal variability in meteoric and *in situ* ^{10}Be ($^{10}Be_m$, $^{10}Be_i$) on sand-sized grains of riverine transported material in landslide-prone basins. We analyzed 20 samples collected over 18 months from the channels of two nested watersheds: the Icacos (3.14 km^2, 0.09% active landslide area) and Guabá basins (0.11 km^2, 1.23% active landslide area). $^{10}Be_i$ concentrations in Icacos basin sediment remained steady over time whereas concentrations in Guabá basin sediment were initially half those in the Icacos basin and increased linearly over 18 months, constraining recovery time to <2 yrs for this basin. $^{10}Be_m$ concentrations in both drainages did not change consistently over time and were not related to precipitation events; $^{210}Pb_{ex}$ and ^{137}Cs were below detection limits in all samples. Our data demonstrate that $^{10}Be_i$ concentrations in river sand can be lowered for months to years after major landscape disturbing events, such as large or extensive mass movements. Sampling soon after a landslide will result in over-estimates of long-term erosion rates. Such bias can be reduced by repeated sampling over time and by sampling numerous similar watersheds of different sizes and different concentrations of landslides in a study area.

1. Introduction

Steep tropical landscapes, such as the Sierra de Luquillo in northeastern Puerto Rico, experience landslides due to high annual rainfall and frequent, intense hurricanes (Larsen and Torres-Sanchez, 1998). Episodic landslides may contribute more to the erosion of such landscapes than distributed processes such as soil creep (Wolman and Gerson, 1978). It is important to constrain what effects landslides have on cosmogenic nuclide concentration in detrital sediments because accurate erosion rate determinations from single samples rely on the assumption of steady isotope concentration in sediment over time (Brown et al., 1995; Bierman and Steig, 1996; Granger et al., 1996). Such an assumption is violated if mass movements episodically contribute large amounts of deeply-sourced, and hence low isotopic concentration, sediment to channels (Niemi et al., 2005; Yanites et al., 2009).

Here, we report *in situ* produced and meteoric ^{10}Be ($^{10}Be_i$ and $^{10}Be_m$, respectively) as well as ^{137}Cs and $^{210}Pb_{ex}$ concentrations in detrital sediment collected from two nested, headwaters basins in northeastern Puerto Rico (Fig. 1), the Río Icacos and its tributary, Quebrada Guabá. Samples were collected at weekly to monthly intervals over 18 months following Hurricane María, a category 4 storm when it hit Puerto Rico in 2017, and thus allow us to quantify the effect of landscape disturbance by a major hurricane. Repli-

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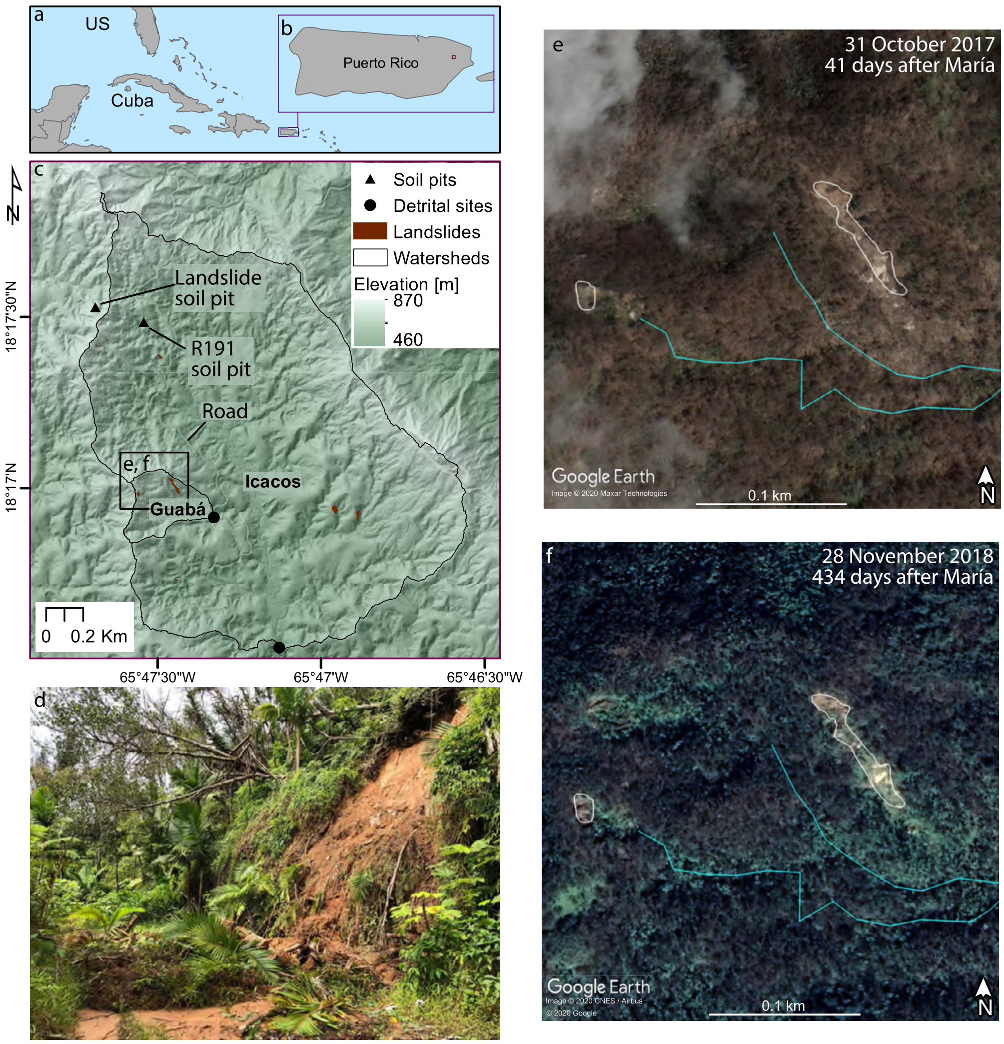

Fig. 1. Map of study location. (a) Location of Puerto Rico and (b) the study area (purple box) in Puerto Rico. (c) Study watersheds. Elevation data from NOAA and USGS (OCM Partners, 2020). We mapped landslides visible in Google Earth imagery taken after Hurricane María at locations of landslides caused by Hurricane María (Hughes et al., 2019). Box shows location of panels (e) and (f). (d) Typical landslide along the road labelled in (c). (e–f) Satellite image of the two landslides in the Guabá (outlined in white) with river channels (blue) 41 days (e) and 434 days (f) after Hurricane María. Images are from Google Earth. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

cate $^{10}Be_i$ measurements in and around these basins from 1995 to 2015 (Brown et al., 1995, 1998; Riebe et al., 2003; Brocard et al., 2015) provide context for the data we present.

2. Background

Concentrations of *in situ* ^{10}Be ($^{10}Be_i$) have been widely used to determine basin-scale erosion rates and track sediment movement down slopes (Bierman et al., 2021). $^{10}Be_i$ accumulates in minerals primarily in the upper several meters of the Earth's surface as a result of interactions with cosmic rays (Lal, 1991). Landslides erode into and through the production profile of $^{10}Be_i$, removing the nuclide-rich shallow sediment and supplying more deeply-sourced, nuclide-poor sediment to rivers (Brown et al., 1995; Niemi et al., 2005; Yanites et al., 2009).

Basins with relatively small and shallow landslide areas can still generate temporally representative concentrations of $^{10}Be_i$ in sediment, because the percentage of material in transit derived from landslides is small (Niemi et al., 2005; Yanites et al., 2009). Large basins, with numerous tributaries, each having different landslide frequencies and timing, are more likely to have buffering capacity sufficient to minimize the impact on sediment $^{10}Be_i$ concentration from isolated landslides (Niemi et al., 2005; Yanites et al., 2009).

In contrast, when landslides affect a large percentage of a watershed or are very deep, they collectively excavate enough deeply sourced material to periodically lower sediment $^{10}Be_i$ concentrations at the basin outlet because landslide material dominates the outgoing sediment flux (Bierman and Steig, 1996). A study of samples collected before and after the 2008 Wenchuan earthquake in Sichuan, China suggests that in the case of major disturbances (affecting >0.5% of the basin area), sufficiently deep landslides can change $^{10}Be_i$ concentration in detrital sediment even in large (>15,000 km^2) basins (West et al., 2014). Landslides can also bias $^{10}Be_i$ concentrations if sampled sediment is sourced from a single landslide at an elevation not representative of the catchment as a whole, such as in the Himalayas (Lupker et al., 2012).

Landslide recovery times are less than a decade for tropical regions to decades or more in temperate regions (Wolman and Gerson, 1978). The duration of landslide impacts on detrital sediment $^{10}Be_i$ concentrations can be modelled (Niemi et al., 2005; Yanites et al., 2009), and models based on the replicate analyses taken after the Wenchuan earthquake indicate a "recovery period" of approximately 2–3 yrs (West et al., 2014). Data following Typhoon Morakot in Taiwan suggest that the effects of landslides remain detectable in $^{10}Be_i$ concentration in detrital sediments after three years (Chen et al., 2019).

Meteoric ^{10}Be ($^{10}Be_m$) is used to trace sediment through watersheds and estimate soil loss (Bierman et al., 2021), as well as to measure erosion rates in combination with reactive ^9Be (von Blanckenburg et al., 2012). Spallation reactions in the atmosphere produce $^{10}Be_m$, which is deposited by precipitation and dryfall and adsorbs to the outside of grains, where it is incorporated in grain coatings (Singleton et al., 2017). Peak concentrations of $^{10}Be_m$ usually occur in the upper meters of the Earth's surface (Graly et al., 2010) and hence can shed light on the depth of erosion.

$^{210}Pb_{ex}$ and ^{137}Cs are short-lived fallout radionuclides often used to fingerprint sediment source. $^{210}Pb_{ex}$ is a product of the ^{238}U decay series, which decays to ^{222}Rn gas and escapes to the atmosphere. ^{137}Cs on the surface of the Earth is a result of atmospheric weapons testing in the 1950s–70s. Both nuclides are only present in the upper ~25 cm of soil; their absence provides a minimum constraint on the depth of erosion over the past decades.

3. Study site

The Icacos and Guabá basins are located in the Sierra de Luquillo (Luquillo Experimental Forest), northeastern Puerto Rico (Fig. 1). The low relief surface that surrounds the Sierra de Luquillo is interpreted as an old shore platform uplifted since the Pliocene, creating incised reaches and large knickpoints in the area (Brocard et al., 2015). Landslides are the primary source of coarse material to rivers while slower hillslope processes are the source of fine grained material (Brown et al., 1995, 1998; Riebe et al., 2003). The Guabá basin is within the Icacos basin, and experiences similar environmental conditions, including landslides.

USGS gauging stations (sites 50075000 and 50074950) are at the basin outlets and water quality sampling is ongoing (McDowell, 2015). The Icacos basin has a mean elevation of 684 m and a basin area of 3.14 km^2, which includes the Guabá basin. The Guabá basin has a mean elevation of 707 m and is 0.11 km^2. The Icacos and Guabá basins are characterized by old-growth primary forest and experience rainfall of >4500 mm/yr (Garcia-Martino et al., 1996). The base of the mountain range has an average temperature between 23.5 °C and 27 °C (Garcia-Martino et al., 1996).

Hurricane María, which made landfall in September of 2017, was the strongest hurricane to hit Puerto Rico since 1928 (NWS, 2017). The combination of heavy rainfall, abundant soil moisture, and flooding triggered ~40,000 landslides in mountainous areas of the island (Hughes et al., 2019). In addition to episodic large events like Hurricane María, each year brings, on average, about one landslide-inducing storm to Puerto Rico (Larsen and Simon, 1993).

Hurricane María caused eight landslides in the Icacos basin, two of which were in the Guabá basin (Hughes et al., 2019). María-induced landslides cover 0.09% of the Icacos basin and 1.23% of the Guabá basin. The two slides in the Guabá basin were ~100 and ~900 m^2; the smaller slide was located on the basin divide in a hollow directly connected to the tributary network while the larger slide was located ~60 m from the nearest channel (Fig. 1e-f). Landslides (Fig. 1d) are common, particularly along the road through the basin (Fig. 1c).

The lithology and geomorphology of the Icacos and Guabá basins may contribute to the frequency of landslides (Borgomeo et al., 2014). The Sierra de Luquillo has a central igneous core (Bessette-Kirton et al., 2019). Both basins are underlain by erodible, weathered quartz diorite bedrock, with widespread saprolite (Buss and White, 2012). This quartz diorite is homogenous and rich in quartz (23% by mass) (Turner et al., 2003). The combination of high temperatures and precipitation causes these watersheds to have some of the fastest documented chemical weathering rates of granitic rock in the world (McDowell and Asbury, 1994; Riebe et al., 2003). This creates weak saprolite and regolith on steep slopes which is amenable to sliding in heavy rains when pore pressures rise.

Estimates of surface lowering in the Icacos basin vary widely depending on whether estimates are based on chemical or physical denudation; estimates range from 0.08–0.20 × 10^6 kg km^{-2} y^{-1} for chemical denudation and 0.17–2.14 × 10^6 kg km^{-2} y^{-1} for physical denudation (McDowell and Asbury, 1994; Larsen, 1997; White et al., 1998; Turner et al., 2003; Larsen, 2012; Stallard and Murphy, 2012). Steady state sediment yield rates are estimated to be 0.1–0.2 × 10^6 kg km^{-2} y^{-1} (Turner et al., 2003; Stallard and Murphy, 2012); modern rates are an order of magnitude higher due to shallow landslides along the road through the basin as shown in Fig. 1 (Larsen, 1997, 2012; Stallard and Murphy, 2012).

$^{10}Be_i$ concentrations in the Sierra de Luquillo have been measured previously several times (Table S1) in undisturbed hillslope sediment, landslide scars, detrital sediment in multiple grain sizes from both the Icacos and the Guabá basins, and exfoliation slabs exposed on ridges (Brown et al., 1995, 1998; Riebe et al., 2003; Brocard et al., 2015). The 2015 measurements of $^{10}Be_i$ in Icacos basin sediment are nearly 30% lower than comparable measurements in 1995 of sediment in the same grain size ($1.71 \times 10^5 \pm 5.50 \times 10^3$ atoms g^{-1} vs $2.35 \times 10^5 \pm 1.89 \times 10^4$ atoms g^{-1} in 1995, adjusted for changes in ^{10}Be standards). Perhaps the difference is due to the road through the basin which has many small slides where it is cut into the hillslope. Measurements made in 2003 are on unsieved sediment and thus cannot be directly compared to those from 1995, 1998, and 2015 because of known variation of nuclide concentration with grain size in this region (Brown et al., 1995).

4. Methods

We collected detrital sediment samples from the Icacos and Guabá basins, upstream of knickpoints, on twenty sampling dates between January 19th, 2018 (121 days after the storm) and May 1st, 2019 (588 days after the storm). Sediment was collected from the wetted portion of the streams to ensure it had been sourced and transported from the basin upstream and not from local streambanks. Most samples were collected on the same date from both watersheds (Table S1). We analyzed seven samples collected soon after large rain events for $^{10}Be_i$ and $^{10}Be_m$, and all twenty for ^{137}Cs and $^{210}Pb_{ex}$. We also report data from samples collected in 2011 from a) surface soil from a broad ridge and b) an excavated, exposed portion of a fresh landslide scar in the Icacos basin, to understand the depth distribution of $^{10}Be_m$ concentrations from the surface through saprolite to a depth of 3.2 m (Table S2).

We extracted $^{10}Be_i$ and $^{10}Be_m$ from seven sieved river sediment samples at the University of Vermont Community Cosmogenic Facility. We isolated quartz from 250–710 μm river sand (Kohl and Nishiizumi, 1992) to extract $^{10}Be_i$ (Corbett et al., 2016). $^{10}Be_m$ was extracted using a modification of the methods described in Stone (1998). We added ~250 μg of ^9Be to each $^{10}Be_i$ and ~400 μg of ^9Be to each $^{10}Be_m$ sample using a carrier made at the University of Vermont with a ^9Be concentration of 304 ppm (Tables S3 and S5).

We extracted $^{10}Be_m$ from surface soil ($n = 3$) and landslide depth profile samples ($n = 7$) sieved to <2 mm at the University of Pennsylvania using methods described in Ebert et al. (2012). At the University of Pennsylvania, we added ~250 μg of ^9Be to each $^{10}Be_m$ sample using a SPEX ICP standard with a concentration of 1000 ppm. (Table S7).

Accelerator mass spectrometry (AMS) analysis of all ^{10}Be samples was completed at the Purdue Rare Isotope Measurement Laboratory (PRIME). Measured ratios were normalized to the 07KN-STD3110 standard with an assumed $^{10}Be/^{9}Be$ ratio of 2.85×10^{-12} (Nishiizumi et al., 2007). $^{10}Be_i$ samples were corrected for background using the mean and standard deviation of four blanks processed around the same time and analyzed in the same AMS run (Table S4). $^{10}Be_m$ in sediment samples was corrected for background using the mean and standard deviation of two blanks processed around the same time and analyzed in the same AMS run (Table S6). Soil samples were corrected for background using the average of three blanks processed around the same time and analyzed in the same AMS run (Table S8).

Samples were analyzed for ^{137}Cs and $^{210}Pb_{ex}$ at Oberlin College (Singleton et al., 2017). No sample had peak areas for either isotope above the critical limit for detection (Supporting Information).

5. Results

$^{10}Be_i$ concentrations in Guabá basin river sand increased linearly from 5.7 to 14.7×10^4 atoms g^{-1} over the 18-month sampling period following Hurricane María ($R^2 = 0.96$, $p < 0.01$) (Fig. 2). $^{10}Be_i$ concentrations in Icacos basin river sand did not vary significantly over the 18-month period (error weighted mean = $15.5 \pm 0.2 \times 10^4$ atoms g^{-1}, $n = 7$, error weighted uncertainty, Table S4). The $^{10}Be_m$ concentration in the Icacos and the Guabá basin sand varied with no clear relationship with time or rainfall amount ($78.6 \pm 19.6 \times 10^6$ and $68.7 \pm 8.1 \times 10^6$ atoms g^{-1}, respectively, $n = 7$ each, mean and 1SD) (Table S6). The $^{10}Be_m$ concentrations in the landslide soil profile (0–320 cm) in the Icacos basin showed no systematic variation with depth ($61.1 \pm 8.1 \times 10^6$ atoms g^{-1}, $n = 7$) (Fig. 3, Table S8). The $^{10}Be_m$ concentrations in a shallow soil profile (0.15 m) were higher ($146 \pm 5 \times 10^6$ atoms g^{-1}, $n = 3$) than in the landslide soil profile.

6. Discussion

Hurricane María, and the landscape change it caused, systematically lowered the concentration of $^{10}Be_i$ in the smaller of two watersheds we sampled (the Guabá basin), because a sufficient volume of landslide-sourced sediment was introduced into the channel to change the $^{10}Be_i$ concentration in the flux of sediment out of the basin. Time series data indicate that the lowered concentration of $^{10}Be_i$ lasted for over 17 months, implying that detrital sediment sampling soon after major hurricanes could result in low measured isotope concentrations that are unrepresentative of the long-term sediment flux.

6.1. Landslides affect the $^{10}Be_i$ in Guabá but not the Icacos basin

The $^{10}Be_i$ concentration for Guabá basin sediment 121 days after María ($5.7 \pm 0.3 \times 10^4$ atoms g^{-1}) is 2X lower than previously measured river sediment at the same location ($12.4 \pm 2.7 \times 10^4$ atoms g^{-1}, $n = 2$, mean and 1SD (Brown et al., 1995)) but greater than $^{10}Be_i$ concentration in landslide material ($3.1 \pm 0.7 \times 10^4$ atoms g^{-1}, $n = 2$). By the end of the 17-month collection period, concentrations in Guabá basin sediment had increased steadily to values ($14.8 \pm 0.5 \times 10^4$ atoms g^{-1}) comparable to but slightly less than $^{10}Be_i$ concentrations in hillslope soils ($17.6 \pm 0.5 \times 10^4$ atoms g^{-1}, $n = 7$) (Brown et al., 1995; Riebe et al., 2003). This suggests that landslide sediment slowly evacuated from the Guabá basin over the sampling period. As more landslide material was removed, the landslide sediment was mixed with hillslope material, leading to linearly increasing $^{10}Be_i$ concentrations.

In the Icacos basin, error weighted average nuclide concentrations of river sand over the 500 days following María ($15.5 \pm 0.2 \times 10^4$ atoms g^{-1}, $n = 7$) are slightly lower than the finer of two medium sand fractions ($17.6 \pm 0.2 \times 10^4$ atoms g^{-1}, 250–500 μm) and significantly higher than the coarser medium sand fraction ($8.4 \pm 0.9 \times 10^4$ atoms g^{-1}, 500–1000 μm) previously measured (Brown et al., 1995). Given that the area has strong grain size dependency in isotopic concentration and our samples contain sediment with grain sizes that span both the size fractions measured by Brown et al. (1995), it is not surprising that the $^{10}Be_i$ concentrations we measure fall between those measured by Brown. However, the two data points reported by Brown et al. (1995) nearly span the entire range between hillslope soils and landslides in the basin, suggesting that there is a high degree in variability of isotopic concentration in Icacos basin sediment.

Previous studies have shown that coarse grain (>1 mm) river sediment samples have $^{10}Be_i$ concentrations similar to landslide material; finer (<1 mm) grained samples have concentrations more like hillslope material (Brown et al., 1995, 1998; Brocard et al., 2015) (Fig. 4a). We measured medium sand (250–710 μm) and find that our samples from the Guabá basin have $^{10}Be_i$ concentrations that linearly increase over time after the hurricane-related landslide events. At the start of sampling, ∼4 months after the hurricane, $^{10}Be_i$ concentrations are similar to landslide material. After 17 months of additional sampling, they are similar to hillslope material (Figs. 2c and 4a).

Our data show that in this watershed, sand-sized material contains a significant proportion of landslide material for at least 18 months after a major landslide event. After 18 months, $^{10}Be_i$ concentrations indicate that most sand is delivered by on-going, diffusive hillslope processes, as previously inferred (Brown et al., 1995, 1998; Brocard et al., 2015).

6.2. Timescale of landslide impacts on sediment

If we assume a simple mixing model between the endmembers of landslide material at a similar grain size (sand) and soil, then Guabá basin sediment contained ∼80% landslide material 121 days after Hurricane María and was 19% landslide material by 588 days after the storm (see supporting materials); extrapolating the linear regression of landslide material as a function of time back to the storm suggests that the Guabá basin sediment was 100% landslide-derived immediately following Hurricane María. The dilution of landslide-sourced material is steady over time (Fig. 2), suggesting it decreases at a rate of ∼1% per week; at that rate, it would take about 700 days for $^{10}Be_i$ concentration in river sand to return to background levels. This suggests a recovery time of ∼2 yrs following the storm for a basin ∼0.1 km^2, in line with estimates made for much larger basins (up to 15,000 km^2) after the Wenchuan Earthquake (West et al., 2014) and after Typhoon Morakot (Chen et al., 2019).

Field and satellite image observations suggest that landslides in the Guabá basin do not fully revegetate and stabilize over 18 months (Walker et al., 1996). Although there are two landslides in the Guabá, the smaller landslide (100 m^2), which is in a colluvial hollow directly connected to the channel network, is likely the primary source of the landslide sediment in our samples.

Based on the difference in concentration of $^{10}Be_i$ in landslide sediment and surface soil, and assuming a density of 2000 kg m^{-3}, we calculate that the landslide was between 3 and 4 m thick, on average. This 100 m^2 slide would have contributed 6 to 8×10^5 kg of sediment to the channel network during Hurricane María. This is 10–12X the annual sediment yield in the Guabá that we can calculate from our final sample (day 588; 5.9×10^5 kg km^{-2} y^{-1} for a 0.1 km^2 basin is 5.9×10^4 kg y^{-1}), suggesting that even a small slide (0.1% of the basin area) that is well connected to the drainage network can make a measurable difference in sediment isotope concentrations.

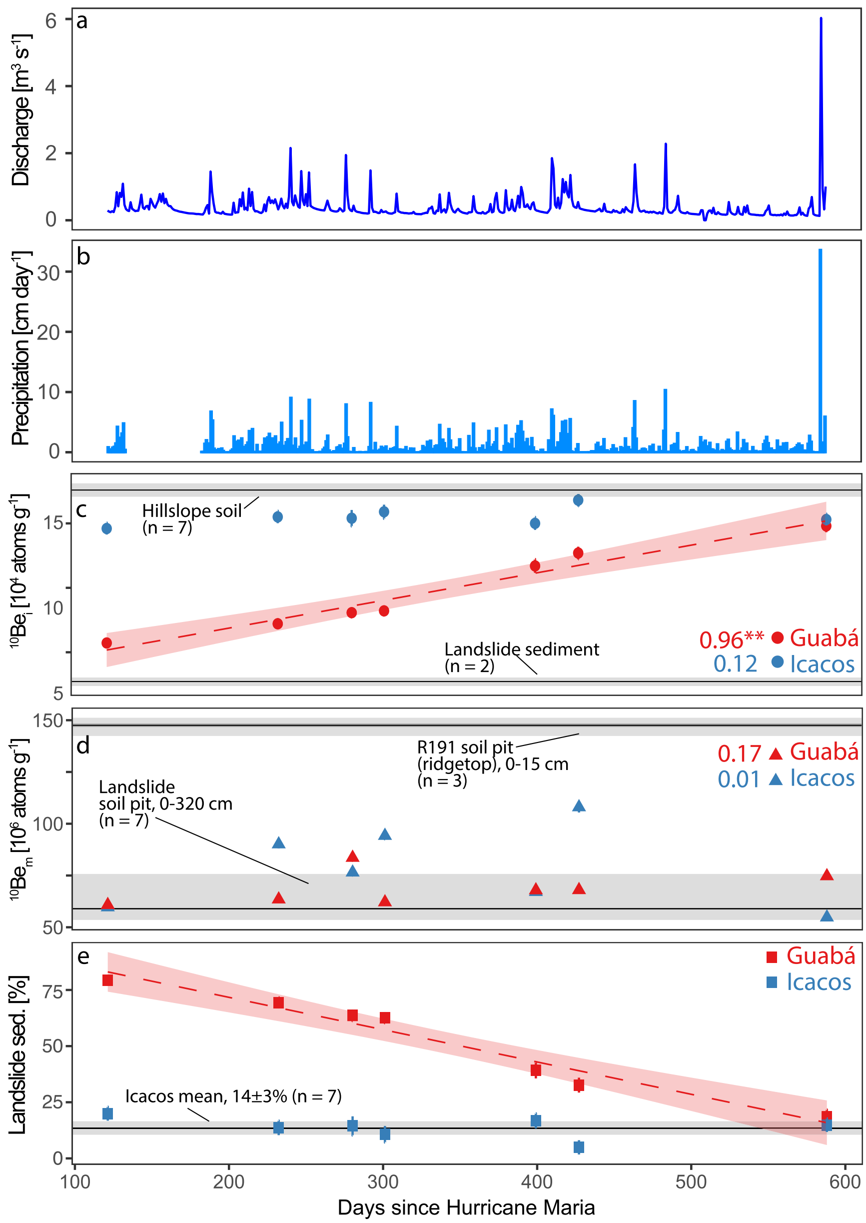

Fig. 2. Trends in (a) discharge (from USGS gauging station at the Icacos sample site, 50075000), (b) precipitation (also from Icacos gauge; data missing for days 133–181), (c) $^{10}Be_i$ (circles), and (d) $^{10}Be_m$ (triangles) during the period in which samples were collected. (e) Percent of sediment modelled as landslide sediment based on the $^{10}Be_i$ concentrations and end-member landslide and soil data for the Icacos (shown in (c)) (Brown et al., 1995; Riebe et al., 2003). Blue represents samples from the Icacos basin and red the Guabá basin. Error bars are 1 SD analytic uncertainty. Inset numbers are R^2 values of the isotopic concentration as a function of time. ** indicates $p < 0.01$. Trendline in panels (c) and (e) are the linear best fit line for the Guabá basin sediment with the 95% confidence interval shown. Grey bars in (c) and (d) are the range of measurements for the soil pits, as labelled; grey bars in (c) are from Brown et al. (1995); and Riebe et al. (2003). Darker line in each grey area is the standard deviation of the data from each soil pit. New soil pit data are shown in Fig. 3. Grey bar in panel (e) is the mean landslide concentration for the Icacos, based on all our data. Data in panels (c) and (d) are available in Tables S3, S5, and S7.

Because all our $^{10}Be_i$ samples were collected soon after large rainstorms, it seems likely that they reflect the results of active evacuation of landslide material that filled a small stream channel. The slow, linear decline in landslide sediment as it exits the Guabá basin is inconsistent with a discrete sediment pulse. Rather, the steady decline in landslide-derived sediment over time is more consistent with on-going excavation of a first order channel overwhelmed during Hurricane María with landslide material originating from a failed colluvial hollow. As more material is removed by high stream discharge events, the remaining sediment in the landslide becomes less connected to the channel, resulting in the pattern of decreasing landslide material sampled at the Guabá outlet over time.

The landscape-wide average recurrence interval for landslides in the Luquillo Mountains is 10 ka (Larsen and Torres-Sanchez, 1992), several orders of magnitude longer than the recovery period that we measured. Landscape-scale estimates of landslide recurrence intervals average areas that slide frequently with those that rarely or never slide. The recurrence interval of sliding on a previous landslide surface will be significantly shorter and is typically controlled by how quickly the landscape accumulates regolith that can slide. Work in other humid locations, where landslide frequency was found to depend primarily on regolith depth in hillslope hollows (Reneau et al., 1990; Parker et al., 2016), is consistent with our interpretation. We speculate that recurrence intervals in this watershed are on the scale of decades to centuries. The larger

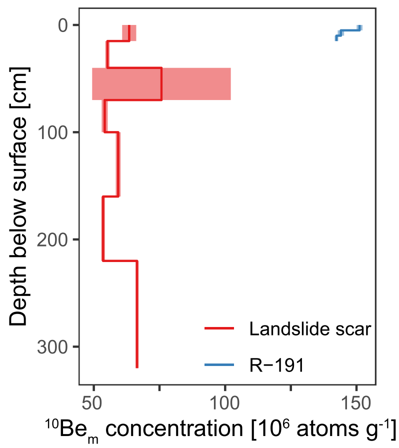

Fig. 3. $^{10}Be_m$ concentration for depth profiles through ridgetop soil (blue, R-191) and regolith in a landslide scar (red). Shaded area is 1 SD analytic uncertainty; for most points analytic uncertainty is smaller than the line width. Data are in Table S2.

of the landslides associated with María in the Guabá basin most recently slid in 2003.

6.3. Role of landslides in sediment source and measured denudation rates

We show here that sediment sourcing changes over time in the Guabá basin, consistent with previously published $^{10}Be_i$ data for the Icacos and Guabá basins that indicate that sediment is not exclusively derived from landslides (Brown et al., 1995, 1998; Riebe et al., 2003; Brocard et al., 2015). Thus, it seems that in this landscape, the sediment source varies over time, similar to how the source of discharge varies over time in catchments (Dunne and Black, 1970). Our data confirm modelling studies suggesting that in areas affected by landslides, random grab samples of sediment could over- or under-estimate representative $^{10}Be_i$ concentrations in river sand and thus $^{10}Be_i$-derived, basin-scale erosion rates depending on time since the last landslide (Yanites et al., 2009).

6.4. The role of landslides in explaining discrepancies among measures of basin-wide denudation rates

Variability among different estimates of basin-wide denudation in the Icacos provides further evidence of the role of landslides in the watershed (Fig. 4b). Mass removal rate estimates from $^{10}Be_i$ in river sand (sediment generation rates; $0.06 \pm 0.02 \times 10^6$ kg km^{-2} y^{-1}, $n = 18$) (Brown et al., 1995, 1998; Brocard et al., 2015) are similar to, but slightly lower than, estimates of chemical weathering from either chemistry of weathering rinds or the dissolved load in rivers ($0.14 \pm 0.05 \times 10^6$ kg km^{-2} y^{-1}, $n = 4$) (Brown et al., 1995; White et al., 1998; Turner et al., 2003; Stallard, 2012). In deeply weathered landscapes, where chemical weathering removes material below the penetration depth of neutrons, $^{10}Be_i$ derived erosion rates underestimate total denudation (e.g., Riebe et al., 2003). This is likely the case in Luquillo, and explains the discrepancy between chemical weathering rates and sediment generation rates.

In contrast, sediment yields calculated from both suspended ($0.7 \pm 0.6 \times 10^6$ kg km^{-2} y^{-1}, $n = 12$) (McDowell and Asbury, 1994; Brown et al., 1995; Larsen, 1997; Stallard and Murphy, 2012) and total (suspended and bedload; $1.0 \pm 0.6 \times 10^6$ kg km^{-2} y^{-1}, $n = 8$) (Larsen, 1997; Stallard and Murphy, 2012) measurements and models in Luquillo are up to an order of magnitude higher than the isotopic or geochemical estimates of denudation (Fig. 4b). Modelling estimates of steady state sediment loads prior to disturbance (0.1–0.2 $\times 10^6$ kg km^{-2} y^{-1}) (Turner et al., 2003; Stallard and Murphy, 2012) are lower than measured loads, but still higher than the $^{10}Be_i$-derived sediment generation rates we and others measured.

Overall, the variability in $^{10}Be_i$-derived sediment generation rates (1 SD $= 0.03 \times 10^6$ kg km^{-2} y^{-1}) is an order of magnitude lower than the difference between the sediment generation rates and modern sediment yield rates (difference in means $= 0.68 \times 10^6$ kg km^{-2} y^{-1}). This suggests that even in this area, which is affected by landslides, $^{10}Be_i$ is useful for determining long-term rates of sediment generation and evaluating the effects of human activity on modern sediment yield rates. Small landslides in the Icacos basin caused by slope cuts made for the roads on steep slopes provide large amounts of wash load silt to the river network; because such slides are shallow (Fig. 1d), they do not significantly alter $^{10}Be_i$-concentration or the derived sediment generation rates, which are remarkably consistent with one another over time and space (Fig. 4b).

6.5. Effects of basin size on changes in isotopic concentration due to landsliding

Although the isotopic data indicate that landslides contributed the majority of the sediment (80%) to the Guabá basin about 4 months after the storm, we see no indication that landslide-sourced sediment (estimated to be from 3–4 m deep landslides) affected the isotope concentration of Icacos basin samples. This implies that the landslide-derived sediment from the Guabá basin is sufficiently diluted by sediment from the 30X larger Icacos basin. Mass balance calculations support these observations. The Guabá basin is ∼3.5% the size of the Icacos basin and our sample from day 588 (∼20% landslide sediment) contributes about 3.5% of the total sediment leaving the Icacos, based on mean values for the Icacos basin. Even if 100% of the sediment leaving the Guabá is from a landslide, this would only account for 20% of the sediment leaving the Icacos. The small percentage of total Icacos basin sediment originating from the Guabá basin should not measurably affect isotopic concentrations in the Icacos basin.

These data support previous modelling studies indicating that the effect of landslides is more pronounced in small basins than large (Niemi et al., 2005; Yanites et al., 2009). Yanites et al. (2009) predicts that basins larger than 100 km^2 can average out landslide effects while Niemi et al. (2005) concludes that landslide effects scale inversely with erosion rate ($A_{ave} = 100/E$, where E is the erosion rate in km Ma^{-1} and A_{ave} is the area required to average out landslide effects in km^2). Using their equation and the average erosion rate calculated in the CRONUS online calculator (Balco et al., 2008) from our error-weighted average concentration of $^{10}Be_i$ for E (0.0195 km Ma^{-1}, Table S5), would suggest basins need to be at least 5300 km^2 in order for erosion rates determined using $^{10}Be_i$ to be unaffected by localized landsliding. $^{10}Be_i$ concentration in the 3.1 km^2 Icacos basin was unaffected by Hurricane María suggesting that considering basin area, mean erosion rate, and area of landslides, as both prior models do, is less relevant than the volume of slid material relative to background sediment loads in the basin.

Our data suggest that the most important parameter to consider is not the basin size but the percentage of sediment exiting the basin contributed by deep-seated landslides, which is a function of the recurrence interval at a given location, the fraction of the basin affected by landslides, and the volume and depth of typical slides. The volumetric fraction of sediment leaving the basin that is caused by a landslide is what determines whether and for how long a landslide signal can be detected in the detrital river sediment $^{10}Be_i$ concentration. In Puerto Rico, landslides are a relatively minor contribution to overall erosion and most slides are

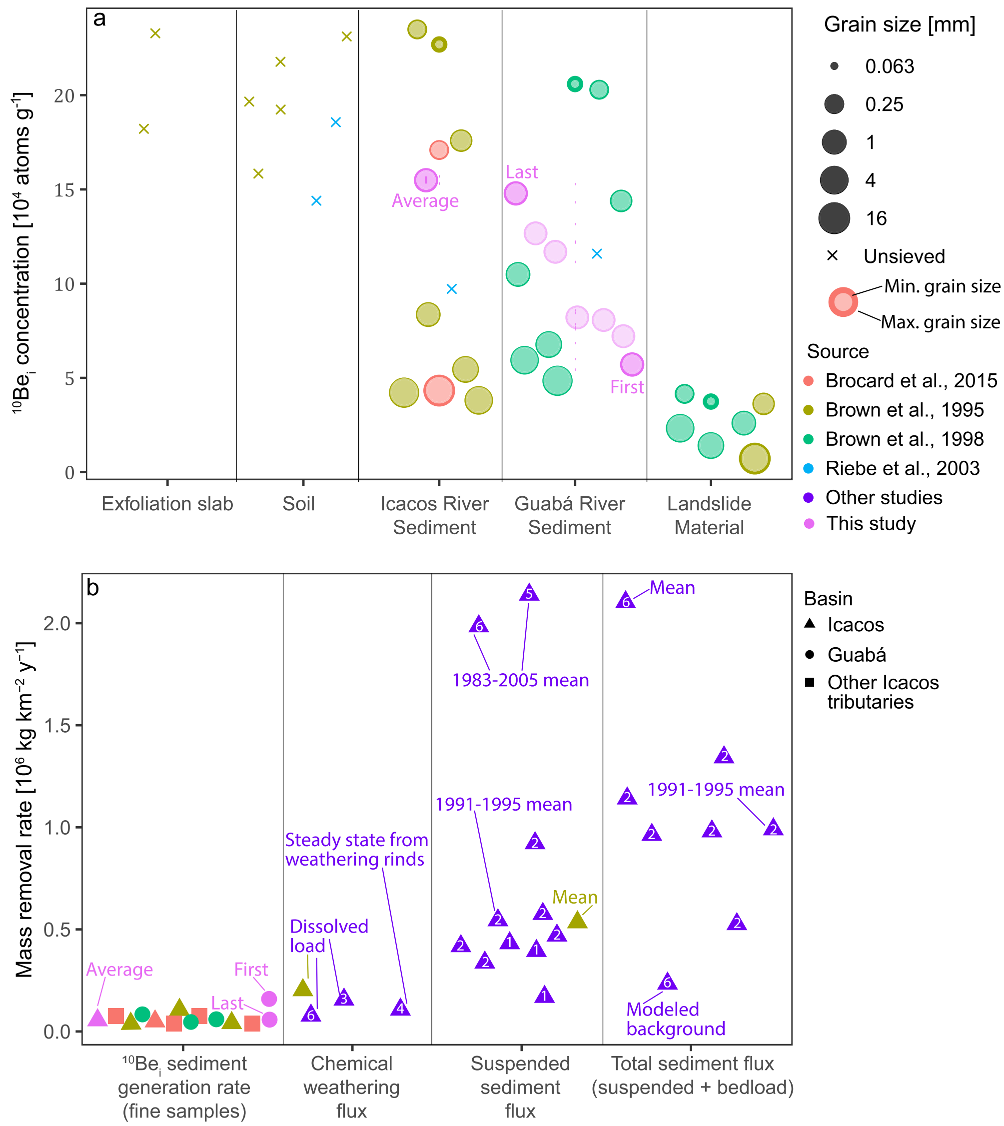

Fig. 4. Comparison of our data with other published data. (a) $^{10}Be_i$ in sediment from different locations in the Icacos basin. Samples are colored by study and sized based on the grain size to which they were sieved. The outer circle indicates maximum grain size; the inner circle is the minimum grain size. Samples marked by x were unsieved. Error bars are not shown for simplicity except for the error-weighted average of all our Icacos basin sediment samples (1 SD shown). All isotope concentrations are adjusted to the KNSTD07 ^{10}Be AMS standard. (b) Mass removal estimates organized by method used for estimate. $^{10}Be_i$ derived sediment generation rates are for samples sieved to between 62.5 and 1000 μm. Colors are the same as in panel (a). Bedload was measured for a few samples and estimated for other samples in the total sediment flux panel. Sources for purple (other) studies are as follows: 1) McDowell and Asbury (1994), 2) Larsen (1997), 3) White et al. (1998), 4) Turner et al. (2003), 5) Larsen (2012), 6) Stallard (2012).

small, shallow and in regolith not rock, meaning that landslides have little effect on $^{10}Be_i$ concentrations most of the time.

6.6. Landsliding impacts detrital $^{10}Be_i$ concentration and apparent erosion rates over time

Using the data that we and others have collected, we investigate the likelihood that grab samples of sediment will over- or under-estimate the long-term average concentration of $^{10}Be_i$ in river sediment. Such a calculation relies on the estimate (based on a linear mixing model of measured $^{10}Be_i$ concentrations in landslide and hillslope sediment that we solved for the mean $^{10}Be_i$ concentration of Icacos sediment) that 14% of material in transport is typically derived from landslides. There are significant grain size dependent variabilities in $^{10}Be_i$ concentration in Puerto Rico (Brown et al., 1995, 1998; Brocard et al., 2015); we only consider medium sand in this analysis.

For a system in which the same amount of landslide sediment is exported over time, all samples will accurately reflect the long-term mean concentration of $^{10}Be_i$ and the only variability will be analytic noise. This is not the case in our data set where analytic precisions for the Icacos data average $3.3 \pm 0.4\%$ but the standard deviation of concentrations we measured in seven samples is 4.5%, about 50% higher. Thus, the concentration of landslide sediment in the Icacos sediment does vary over time, but not substantially.

Using the measured Icacos basin time series, and the endmembers listed above in combination with the same linear mixing model, we infer the fraction of medium sand leaving the basin that is derived from landslides is 5–20% (mean $= 14 \pm 3\%$, mean and 1 SD) (Fig. 2e). Even after a major hurricane, only small changes in isotope concentration are "normal" for the Icacos basin system and are probably driven by changes in the amount of landslide sediment delivered to the channel and transported out of the basin

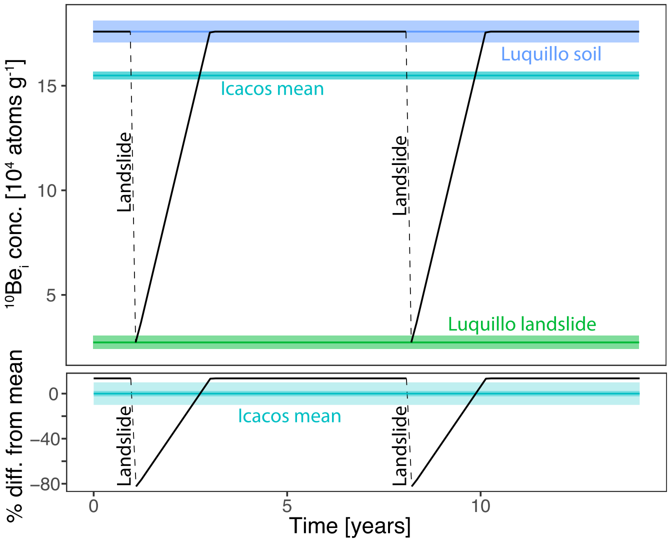

Fig. 5. End-member model of the Icacos basin where one landslide, which takes ~2 yrs to be removed from the system, happens each 7 yrs. The shape of the recovery from the landslide is the best fit regression for data we measured in the Guabá basin. In this model the long-term mean concentration of $^{10}Be_i$ is the same as the measured mean concentration, but the "correct" concentration is only reflected in sediment 6% of the time.

over time (presuming hillslope $^{10}Be_i$ concentrations are spatially homogenous).

A simple model shows the extent to which estimates of erosion from a single grab sample taken within a few years after a landslide event can vary (Fig. 5). Using the hillslope and landslide sediment endmembers (17.5×10^4 and 2.7×10^4 atoms g^{-1} respectively), we assume the response time of the Guabá basin (1% per week recovery) with 100% hillslope sediment contributed between landslides and landslides initially contributing 100% of sediment to the river. To reach the average of 14% landslide material over long periods of time requires a seven-year recurrence interval of landslides. In such a system, 94% of the time the concentration of $^{10}Be_i$ in the river channel will be more than 10% different from the long-term average concentration; 73% of the time the concentration will be too high (too much hillslope material, up to 13.5% too high) and 11% of the time it will be too low (too much landslide material, up to 80% too low). We conclude that measuring between slide cycles gives a slight underestimate of long-term erosion rates whereas measuring soon after a landslide is likely to result in significantly overestimating the long-term, basin average erosion rate.

Most fluvial systems lie between the end-members of well-mixed sediment and pulsed delivery of landslide-derived material. The narrow range of landslide contributions that we measure in the larger Icacos (5–20%, mean $= 14 \pm 3\%$) suggests that the Icacos remained relatively well mixed even after a major hurricane like María. In contrast, the smaller Guabá is much less well mixed (evolving from 80 to 19% landslide material over 18 months). Basin size and landslide volume are clearly important controls on variability in $^{10}Be_i$ concentration over time, but the connectivity of hillslopes and the river channel are also important because such connectivity determines how efficiently landslide material enters the channel (Li et al., 2016). This is exemplified in the Guabá, where a second María-induced landslide is not connected to the channel.

Our simple interpretive model illustrates how understanding the sediment sourcing dynamics in watersheds over time prior to sampling provides important context. Knowing the depth and volume of landslides as well as their recurrence interval can inform whether it is useful to take multiple samples over longer periods of time or to sample many smaller catchments in a region in order to accurately estimate long-term average concentrations of $^{10}Be_i$ in sediment leaving a watershed.

6.7. Differences between isotopic systems

The response of $^{10}Be_m$ and $^{10}Be_i$ concentrations in Guabá basin river sand differ because $^{10}Be_m$ and $^{10}Be_i$ concentration depth profiles in the regolith from which landslide sediment is sourced are dissimilar. $^{10}Be_m$ concentrations, controlled by $^{10}Be_m$ transport through the soil profile and soil mixing, vary little over a range of >3 m depth (Fig. 3). In contrast, $^{10}Be_i$ concentrations with depth are determined by cosmic ray attenuation and bioturbation by animals and plant roots, ultimately decreasing by three meters depth to $<5\%$ of surface values.

Unlike many $^{10}Be_m$ profiles that show either a subsurface bulge profile or exponential decrease in $^{10}Be_m$ concentration with depth (Graly et al., 2010), there is no systematic change in the $^{10}Be_m$ concentrations with depth in the Guabá basin depth profile (Fig. 3) – even through two meters of intact saprolite. This is consistent with profiles measured in other warm and humid settings, including tropical Taiwan, Brazil, and the wetter parts of Hawaii, which also have relatively little variation in $^{10}Be_m$ concentration profiles with depth below the surface (You et al., 1988; Brown et al., 1992; Graly et al., 2010; Dixon et al., 2018). Together, these data suggest that there may be little variance of $^{10}Be_m$ with depth in certain climates. The lack of a clear depth profile in deeply weathered (humid) tropical soils limits the utility of $^{10}Be_m$ for sediment tracing related to sourcing depth in humid, tropical watersheds.

The low concentrations of short-lived ^{137}Cs and $^{210}Pb_{ex}$ in our measurements indicate that the collected sediment was sourced deeper than the depth at which these short-lived nuclides penetrate soil profiles, which is about 25 cm in undisturbed environments. At the low erosion rates we measured (~20 m Ma^{-1}) in a forested landscape, it is unlikely that anthropogenic activity or natural erosion processes have stripped the top 25 cm of soil from the environment over the past ~60 yrs, when human activity in the Icacos basin has been minimal (McDowell et al., 2012). Thus, we conclude that the absence of detectable ^{137}Cs and $^{210}Pb_{ex}$ implies that sediment is sourced from below the mixed surface layer. However, without knowledge of the grain size distribution of ^{137}Cs and $^{210}Pb_{ex}$ (Singleton et al., 2017) in this location, we cannot exclude the possibility that most of these nuclides are adsorbed to finer sediments.

7. Implications

Our data suggest that in areas with recent extreme storms and subsequent landsliding, sampling for basin-average erosion rates could generate biased data (Fig. 5) unless (a) landslides contribute a small percentage of the sediment leaving the basin or (b) sufficient time has elapsed since the storm and landslides such that isotope concentrations in river sediment reflect a return to hillslopes as the dominant source of sediment. However, if storms and the resulting landslides are frequent and elevations within a watershed do not vary considerably in isotopic content, then the bias would be less. Our data suggest that the relative volume of sediment contributed by a landslide at a single point in time is the primary factor determining whether a landslide affects measured concentrations of $^{10}Be_i$, and thus models of landslide effects will be more realistic if they consider volume rather than average erosion rate, basin area, or fraction of the watershed covered by landslides.

We find that in a small, humid, tropical basin (<1 km^2), $^{10}Be_i$ concentrations in river sand are lowered for months to years after a landslide. Initially, material in transport is dominated by that sourced from the slide. As time passes, a greater percentage of the material is from slopes. Sampling soon after a landslide, within a year or two for our study area, would result in over-estimates of long-term erosion rates of basin slopes. Such bias could be reduced by repeated sampling over time and by sampling numerous similar watersheds of different sizes in a study area to understand regional rates of erosion.

CRediT authorship contribution statement

Alexandra Grande: Investigation, Writing – original draft, Writing – review & editing. **Amanda H. Schmidt:** Conceptualization, Data curation, Formal analysis, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Paul R. Bierman:** Resources, Supervision, Writing – original draft, Writing – review & editing. **Lee B. Corbett:** Investigation, Methodology, Validation, Writing – review & editing. **Carla López-Lloreda:** Investigation, Writing – review & editing. **Jane Willenbring:** Investigation, Methodology, Resources, Writing – review & editing. **William H. McDowell:** Resources, Writing – review & editing. **Marc W. Caffee:** Investigation, Methodology, Resources, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2021.116821.

References

Balco, G., Stone, J.O., Lifton, N.A., Dunai, T.J., 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from Be-10 and Al-26 measurements. Quat. Geochronol. 3, 174–195.

Bessette-Kirton, E.K., Cerovski-Darriau, C., Schulz, W.H., Coe, J.A., Kean, J.W., Godt, J.W., Thomas, M.A., Hughes, K.S., 2019. Landslides triggered by Hurricane Maria: assessment of an extreme event in Puerto Rico. GSA Today 29, 4–10.

Bierman, P.R., Bender, A.M., Christ, A.J., Corbett, L.B., Halsted, C.T., Portenga, E.W., Schmidt, A.H., 2021. Dating by cosmogenic nuclides. In: Alderton, D., Elias, S.A. (Eds.), Encyclopedia of Geology, second edition. Academic Press, Oxford, pp. 101–115.

Bierman, P.R., Steig, E.J., 1996. Estimating rates of denudation using cosmogenic isotope abundances in sediment. Earth Surf. Process. Landf. 21, 125–139.

Borgomeo, E., Hebditch, K.V., Whittaker, A.C., Lonergan, L., 2014. Characterising the spatial distribution, frequency and geomorphic controls on landslide occurrence, Molise, Italy. Geomorphology 226, 148–161.

Brocard, G.Y., Willenbring, J.K., Scatena, F.N., Johnson, A.H., 2015. Effects of a tectonically-triggered wave of incision on riverine exports and soil mineralogy in the Luquillo Mountains of Puerto Rico. Appl. Geochem. 63, 586–598.

Brown, E.T., Edmond, J.M., Raisbeck, G.M., Bourlès, D.L., Yiou, F., Measures, C.I., 1992. Beryllium isotope geochemistry in tropical river basins. Geochim. Cosmochim. Acta 56, 1607–1624.

Brown, E.T., Stallard, R.F., Larsen, M.C., Bourlès, D.L., Raisbeck, G.M., Yiou, F., 1998. Determination of predevelopment denudation rates of an agricultural watershed (Cayaguas River, Puerto Rico) using in-situ-produced 10 Be in river-borne quartz. Earth Planet. Sci. Lett. 160, 723–728.

Brown, E.T., Stallard, R.F., Larsen, M.C., Raisbeck, G.M., Yiou, F., 1995. Denudation rates determined from the accumulation of in situ-produced Be-10 in the Luquillo Experimental Forest, Puerto-Rico. Earth Planet. Sci. Lett. 129, 193–202.

Buss, H.L., White, A.F., 2012. Weathering processes in the Icacos and Mameyes watersheds in eastern Puerto Rico. In: Water Quality and Landscape Processes of Four Watersheds in Eastern Puerto Rico, pp. 249–262. Professional Paper 1789.

Chen, C.Y., Willett, S.D., Joshua West, A., Dadson, S., Hovius, N., Christl, M., Shyu, J.B.H., 2019. The impact of storm-triggered landslides on sediment dynamics and catchment-wide denudation rates in the southern Central Range of Taiwan following the extreme rainfall event of Typhoon Morakot. Earth Surf. Process. Landf.

Corbett, L.B., Bierman, P.R., Rood, D.H., 2016. An approach for optimizing in situ cosmogenic ^{10}Be sample preparation. Quat. Geol. 33, 24–34.

Dixon, J.L., Chadwick, O.A., Pavich, M.J., 2018. Climatically controlled delivery and retention of meteoric 10Be in soils. Geology 46, 899–902.

Dunne, T., Black, R.D., 1970. Partial area contributions to storm runoff in a small new-England watershed. Water Resour. Res. 6, 1296–1311.

Ebert, K., Willenbring, J., Norton, K.P., Hall, A., Hättestrand, C., 2012. Meteoric 10Be concentrations from saprolite and till in northern Sweden: implications for glacial erosion and age. Quat. Geochronol. 12, 11–22.

Garcia-Martino, A.R., Warner, G.S., Scatena, F.N., Civco, D.L., 1996. Rainfall, runoff and elevation relationships in the Luquillo Mountains of Puerto Rico. Caribb. J. Sci. 32, 413–424.

Graly, J.A., Bierman, P.R., Reusser, L.J., Pavich, M.J., 2010. Meteoric ^{10}Be in soil profiles - a global meta-analysis. Geochim. Cosmochim. Acta 74, 6814–6829.

Granger, D.E., Kirchner, J.W., Finkel, R., 1996. Spatially averaged long-term erosion rates measured from in situ-produced cosmogenic nuclides in alluvial sediment. J. Geol. 104, 249–257.

Hughes, K.S., Bayouth García, D., Martinez Milian, G.O., Schulz, W.H., Baum, R.L., 2019. Map of slope-failure locations in Puerto Rico after Hurricane Maria. U.S. Geological Survey Data Release. https://doi.org/10.5066/P9BVMD74.

Kohl, C.P., Nishiizumi, K., 1992. Chemical isolation of quartz for measurement of insitu-produced cosmogenic nuclides. Geochim. Cosmochim. Acta 56, 3583–3587.

Lal, D., 1991. Cosmic-ray labeling of erosion surfaces - insitu nuclide production-rates and Erosion models. Earth Planet. Sci. Lett. 104, 424–439.

Larsen, M.C., 1997. Tropical geomorphology and geomorphic work: a study of geomorphic processes and sediment and water budgets in montane humid-tropical forested and developed watersheds, Puerto Rico. Geography, University of Colorado, Boulder, Boulder, CO, p. 341.

Larsen, M.C., 2012. Landslides and sediment budgets in four watersheds in eastern Puerto Rico. In: Water Quality and Landscape Processes of Four Watersheds in Eastern Puerto Rico, pp. 153–178. Professional Paper 1789.

Larsen, M.C., Simon, A., 1993. A rainfall intensity-duration threshold for landslides in a humid-tropical environment, Puerto Rico. Geogr. Ann., Ser. A, Phys. Geogr. 75, 13–23.

Larsen, M.C., Torres-Sanchez, A.J., 1992. Landslides triggered by hurricane Hugo in eastern Puerto Rico, September 1989, Caribb. J. Sci. 28, 113–125.

Larsen, M.C., Torres-Sanchez, A.J., 1998. The frequency and distribution of recent landslides in three montane tropical regions of Puerto Rico. Geomorphology 24, 309–331.

Li, G., West, A.J., Densmore, A.L., Hammond, D.E., Jin, Z., Zhang, F., Wang, J., Hilton, R.G., 2016. Connectivity of earthquake-triggered landslides with the fluvial network: implications for landslide sediment transport after the 2008 Wenchuan earthquake. J. Geophys. Res., Earth Surf. 121, 703–724.

Lupker, M., Blard, P.H., Lave, J., France-Lanord, C., Leanni, L., Puchol, N., Charreau, J., Bourles, D., 2012. Be-10-derived Himalayan denudation rates and sediment budgets in the Ganga basin. Earth Planet. Sci. Lett. 333, 146–156.

McDowell, W.H., 2015. Chemistry of Stream Water from the Luquillo Mountains.

McDowell, W.H., Asbury, C.E., 1994. Export of carbon, nitrogen, and major ions from three tropical montane watersheds. Limnol. Oceanogr. 39, 111–125.

McDowell, W.H., Scatena, F.N., Waide, R.B., Brokaw, N., Camilo, G.R., Covich, A.P., Crowl, T.A., González, G., Greathouse, E.A., Klawinski, P., 2012. Geographic and ecological setting of the Luquillo Mountains. In: Brokaw, N., Crowl, T., Lugo, A., McDowell, W., Scatena, F., Waide, R., Willig, M. (Eds.), A Caribbean Forest Tapestry: The Multidimensional Nature of Disturbance and Response. Oxford University Press, pp. 72–163.

Niemi, N.A., Oskin, M., Burbank, D.W., Heimsath, A.M., Gabet, E., 2005. Effects of bedrock landslides on cosmogenically determined erosion rates. Earth Planet. Sci. Lett. 237, 489–498.

Nishiizumi, K., Imamura, M., Caffee, M.W., Southon, J.R., Finkel, R.C., McAninch, J., 2007. Absolute calibration of Be-10 AMS standards. Nucl. Instrum. Methods Phys. Res., Sect. B, Beam Interact. Mater. Atoms 258, 403–413.

NWS, 2017. Major Hurricane Maria – September 20, 2017. National Weather Service.

OCM Partners, 2020. 2016–2017 USGS Lidar DEM: Puerto Rico from 2010-06-15 to 2010-08-15. In: Information, N.N.C.f.E. (Ed.), https://inpurt.nmfs.noaa.gov/inport/item/55314.

Parker, R.N., Hales, T.C., Mudd, S.M., Grieve, S.W., Constantine, J.A., 2016. Colluvium supply in humid regions limits the frequency of storm-triggered landslides. Sci. Rep. 6, 1–7.
Reneau, S.L., Dietrich, W.E., Donahue, D.J., Jull, A.T., Rubin, M., 1990. Late quaternary history of colluvial deposition and erosion in hollows, central California Coast Ranges. Geol. Soc. Am. Bull. 102, 969–982.
Riebe, C.S., Kirchner, J.W., Finkel, R.C., 2003. Long-term rates of chemical weathering and physical erosion from cosmogenic nuclides and geochemical mass balance. Geochim. Cosmochim. Acta 67, 4411–4427.
Singleton, A.A., Schmidt, A.H., Bierman, P.R., Rood, D.H., Neilson, T.B., Greene, E.S., Bower, J.A., Perdrial, N., 2017. Effects of grain size, mineralogy, and acid-extractable grain coatings on the distribution of the fallout radionuclides ^{7}Be, ^{10}Be, ^{137}Cs, and ^{210}Pb in river sediment. Geochim. Cosmochim. Acta 197, 71–86.
Stallard, R.F., 2012. Weathering, landscape equilibrium, and carbon in four watersheds in eastern Puerto Rico. In: Stallard, R.F., Murphy, S. (Eds.), Water Quality and Landscape Processes of Four Watersheds in Eastern Puerto Rico. US Geological Survey. Chapter H.
Stallard, R.F., Murphy, S., 2012. Weathering, landscape equilibrium, and carbon in four watersheds in eastern Puerto Rico. In: Water Quality and Landscape Processes of Four Watersheds in Eastern Puerto Rico, pp. 199–248. Professional Paper 1789.
Stone, J., 1998. A rapid fusion method for separation of beryllium-10 from soils and silicates. Geochim. Cosmochim. Acta 62, 555–561.
Turner, B.F., Stallard, R.F., Brantley, S.L., 2003. Investigation of in situ weathering of quartz diorite bedrock in the Rio Icacos basin, Luquillo Experimental Forest, Puerto Rico. Chem. Geol. 202, 313–341.
von Blanckenburg, F., Bouchez, J., Wittmann, H., 2012. Earth surface erosion and weathering from the Be-10 (meteoric)/Be-9 ratio. Earth Planet. Sci. Lett. 351, 295–305.
Walker, L.R., Zarin, D.J., Fetcher, N., Myster, R.W., Johnson, A.H., 1996. Ecosystem development and plant succession on landslides in the Caribbean. Biotropica, 566–576.
West, A.J., Hetzel, R., Li, G., Jin, Z., Zhang, F., Hilton, R.G., Densmore, A.L., 2014. Dilution of 10Be in detrital quartz by earthquake-induced landslides: implications for determining denudation rates and potential to provide insights into landslide sediment dynamics. Earth Planet. Sci. Lett. 396, 143–153.
White, A.F., Blum, A.E., Schulz, M.S., Vivit, D.V., Stonestrom, D.A., Larsen, M., Murphy, S.F., Eberl, D., 1998. Chemical weathering in a tropical watershed, Luquillo Mountains, Puerto Rico: I. Long-term versus short-term weathering fluxes. Geochim. Cosmochim. Acta 62, 209–226.
Wolman, M.G., Gerson, R., 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surf. Process. Landf. 3, 189–208.
Yanites, B.J., Tucker, G.E., Anderson, R.S., 2009. Numerical and analytical models of cosmogenic radionuclide dynamics in landslide-dominated drainage basins. J. Geophys. Res., Earth Surf. 114.
You, C.-F., Lee, T., Brown, L., Shen, J., Chen, J., 1988. Be study of rapid erosion in Taiwan. Geochim. Cosmochim. Acta 52, 2687–2691.