Evidence for Erosional Efficiency of Extreme Precipitation Events at a Multi-Decennial Time Scale

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Abstract

Extreme precipitation events play a pivotal role in shaping Earth’s surface through their influences on hillslope processes and sediment transport in rivers. In this study, we focus on understanding the implications of such events on sediment transport, using Réunion Island as a natural laboratory due to its intense tropical rainfall regime. Through photogrammetric techniques and subsequent sediment volume estimates spanning decades as well as cosmogenic ³He measurements, we assessed the spatio-temporal evolution of the canyon bed of the ephemeral Rivière des Remparts and the drainage of products from major landslides and/or rock avalanches between 1950 and 2011. Results show that 39.6 Mm³ of sediment was transported out of the watershed in 62 years. Furthermore, we modeled the flow dates of this ephemeral river and show that such an export of material actually happened during only 391 days over the 62 years, at an average rate of 0.1 Mm³/day. Our investigation confirms that sediment transport coincides with officially recorded extreme meteorological events such as cyclones. Moreover, our findings reveal that sediment transport predominantly occurs on days corresponding to high-percentile rank precipitation events, demonstrating that all transport is concentrated during these intense rainfall periods. Finally, this study underscores the extremely fast conveyance of material from slopes to deep-sea fans, facilitated in Réunion by the absence of a coastal platform. This rapid transfer has implications for CO₂ consumption, as it should enhance the transport and burial of organic matter particles, potentially contributing significantly to the island’s overall CO₂ consumption efficiency.

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Evidence for Erosional Efficiency of Extreme Precipitation Events at a Multi-Decennial Time Scale

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Key Points:

- Under tropical intense rainfall condition, landslide products are evacuated in a matter of days in Réunion Island.
- In Rivière des Remparts, major landslides contributed 82.6 Mm$^3$ to the ephemeral river which evacuated 48% of this sediment in 391 days.
Abstract

Extreme precipitation events play a pivotal role in shaping Earth's surface through their influences on hillslope processes and sediment transport in rivers. In this study, we focus on understanding the implications of such events on sediment transport, using Réunion Island as a natural laboratory due to its intense tropical rainfall regime. Through photogrammetric techniques and subsequent sediment volume estimates spanning decades as well as cosmogenic $^3$He measurements, we assessed the spatio-temporal evolution of the canyon bed of the ephemeral Rivière des Remparts and the drainage of products from major landslides and/or rock avalanches between 1950 and 2011. Results show that 39.6 Mm$^3$ of sediment was transported out of the watershed in 62 years. Furthermore, we modeled the flow dates of this ephemeral river and show that such an export of material actually happened during only 391 days over the 62 years, at an average rate of 0.1 Mm$^3$/day. Our investigation confirms that sediment transport coincides with officially recorded extreme meteorological events such as cyclones. Moreover, our findings reveal that sediment transport predominantly occurs on days corresponding to high-percentile rank precipitation events, demonstrating that all transport is concentrated during these intense rainfall periods. Finally, this study underscores the extremely fast conveyance of material from slopes to deep-sea fans, facilitated in Réunion by the absence of a coastal platform. This rapid transfer has implications for CO$_2$ consumption, as it should enhance the transport and burial of organic matter particles, potentially contributing significantly to the island's overall CO$_2$ consumption efficiency.

Plain Language Summary

In this study, we explore how intense rainstorms shape the landscape and move sediment in rivers. Using Réunion Island as natural laboratory for its heavy tropical rainfall, we examined the changes in riverbeds and sediment transport over several decades in the Rivière des Remparts canyon. By measuring sediment levels from historical aerial images between 1950 and 2011, we found that 39.6 million cubic meters of sediment were carried away by the river over 62 years. Surprisingly, this happened only on 391 days during that time, mainly during cyclones and intense rainfall events. This rapid movement of sediment from slopes to the deep ocean may have significant implications for Reunion island's overall carbon dynamics. In conclusion, our findings shed light on how extreme weather shapes landscapes and impacts the environment.
1. Introduction

The erosion of Earth's surface through hillslope processes and sediment transport in rivers, is significantly influenced by extreme precipitation events. On the one hand, extreme rainfalls trigger or create favorable conditions for landslides that deliver sediments to river channels at the base of the slopes, and promote weathering (Allemand et al., 2014; Emberson et al., 2018; Iverson, 2000; Magilligan et al., 2014; Michon et al., 2023). On the other hand, extreme precipitation events generate high-discharge floods capable of mobilizing substantial sediment loads, and of promoting river incision (e.g., Darby et al., 2016; Lague et al., 2005; Wolman & Miller, 1960). While soil moisture typically buffers the relationship between precipitation and sediment discharge, very intense rainfalls can rapidly saturate the soil, leading to direct and high runoff (e.g., Brunner et al., 2021). These high magnitude and low-frequency floods only accentuate the river's capacity to export the products of the physical erosion and the chemical weathering of the surrounding hillslopes (Croissant et al., 2017; Gaillardet et al., 1999; Louvat & Allègre, 1997; Roque-Bernard et al., 2023), with implications for river and coastal ecosystem health (e.g., Rogers, 1990; Sun et al., 2022).

Understanding and quantifying the impact of extreme precipitation events on slope processes and transport has long been an important issue, given its significance for geomorphology, hydrology, ecology, societal well-being through geomorphological risk management and in the context of global warming (e.g., Na et al., 2020; Pendergrass et al., 2019). Yet, while extreme precipitation floods serve as primary drivers of soil erosion and river channel processes in semi-arid climates (e.g., Coppus & Imeson, 2002; Mulligan, 1998; Osterkamp & Friedman, 2000), their influence remains ambiguous in broader climatic contexts (e.g., Phillips & Jerolmack, 2016; Sambrook Smith et al., 2010; Wolman & Gerson, 1978).

Here we use an ephemeral tropical river on Réunion Island as a natural laboratory and apply photogrammetric techniques to estimate the multidecadal transport rate of floods triggered by extreme rainfall events. Réunion’s steep morphology is notably related to its intense tropical rainfall regime with contrasted seasonality and with cyclones-related rainfalls that hold world records (e.g., 3930 mm in three days during tropical cyclone Gamede in 2007; Garcin et al., 2005; Gayer et al., 2019; Météo-France). Such extreme precipitation events are responsible for
important floods and landslides. For instance, in May 1965, one day after heavy rainfall, 900 m of the scarp of the Riviere des Remparts (RdR) watershed collapsed, leaving a volume of $46 \pm 13 \text{Mm}^3$ of debris (Michon et al., 2023) to be drained by the river. Despite numerous methods available for estimating sediment transport rates, including sediment concentration measurements (Gippel, 1989; Leopold & Emmett, 1976; Liu et al., 2008; Truhlar, 1978), acoustic and seismic noise measurements (Burtin et al., 2016), sediment tracers (Allemand et al., 2023; Phillips & Jerolmack, 2014), and image-processing monitoring (Allemand et al., 2014), calibration and/or application in highly dynamic systems exposed to intense, low-frequency rainfall and floods remain challenging. In this study, we used shape-from-motion photogrammetry for topography reconstruction and calculated differences between Digital Elevation Models (DEMs). By reconstructing nine DEMs from historical aerial images spanning from 1950 to 2011, alongside employing cosmogenic $^3\text{He}$ as a source tracer, we estimated sediment volumes and transport rates within the RdR canyon over decadal timeframes. Furthermore, we compared these findings with precipitation data to quantify the impact of extreme rainfall events on the source-to-sink processes.

2. Geological setting, valley geometry and climate

The RdR canyon is situated on the southern flank of the Piton de la Fournaise volcano, the active volcano of Réunion Island, located 700 km east of Madagascar (Fig. 1a). Since ~ 60 ka and its disconnection from the main eruptive center (Merle et al., 2010), the $60 \text{ km}^2$ RdR watershed has been carved into a deep canyon, characteristic of Réunion’s dissected landscape (Garcin et al., 2005; Gayer et al., 2019). Erosion incised a ~1500 m thick pile of massive layers of 'a'a and pāhoehoe lava flows and interbedded breccias (Bachèlery & Mairine, 1990; Merle et al., 2008, 2010; Michon et al., 2023). The main valley, 24 km in length and oriented N-S, is connected to the east with three shorter northeast-trending tributaries (Bras Caron, Bras de Mahavel, and Bras Dimitile) giving the catchment an overall asymmetrical geometry (Fig. 1b). The RdR canyon is bounded by steep cliffs ranging from 100 to 1400 m in height that reach a highest elevation of 2330 m on the eastern bank. The width of the main valley floor varies between 500 and 100 m, narrowing significantly to below 50 m near the outlet and the canyon exhibits a sinuosity of 1.24. The Bras de Mahavel is the largest tributary, spanning
approximately 4 km in length and having an 8.5 km$^2$ extent (Fig. 1b; Michon et al., 2023). It is characterized by a 1 km long, 700-900 m deep gorge, with a narrow floor, approximately 50 m wide. The intermediate section of the tributary features a linear 1.8 km long valley floor of 700-750 m in width (Michon et al., 2023). Finally, the confluence section, 400 m wide, connects Bras de Mahavel to the upstream part of the main valley at a 120-degree angle resulting in a 14 km long valley (Fig. 1b).

Réunion Island has a tropical climate with strong seasonality between wet and dry seasons. Major cyclones affect the island approximately every 3 years (Gayer et al., 2019; Météo-France), leading to significant floods, landslides, and high rates of physical erosion and chemical weathering (Gayer et al., 2019; Louvat & Allègre, 1997). The RdR catchment, located on the windward side of the island and bordering the leeward side, receives an average rainfall of 2.5 to 4 m per year, depending on altitude. Similar to other basins on the island, the RdR catchment is susceptible to cyclones, resulting in intense rainfall of up to 97 mm/hour (cyclone Firinga; Météo-France), which greatly impacts the river's hydrology. However, unlike the other major rivers on the island, the RdR is ephemeral, flowing only during parts of the year when high precipitation rates cause the water table to rapidly rise producing channel flooding. No discharge records are available for this ephemeral stream although the inhabitants report between 5 and 7 days of flooding per year. Yet, from sparse measurements of the river discharge taken at the watershed's outlet, where the river is perennial over its last 3 km, Violette et al. (1997) estimated that only 30% of the rainfall contribute to the surface flow due to an especially high deep infiltration rate over the entire watershed (accounting for 41% of the rainfall, Violette et al., 1997).
Figure 1. Rivière des Remparts watershed. a) Shaded relief map of the southeastern part of Réunion (UTM 40S), indicating the location of the RdR watershed outlined in red. Purple circles represent the location of the rain gauges stations used for rainfall analysis (a plain circle indicates the Grand Coude station. b) Zoom on the RdR watershed. The main river and tributaries are shown in blue dashed lines, while the active canyon bed is colored light blue. Green circles indicate the sampling sites for cosmogenic $^{3}$He analysis. c) Segmentation of the canyon bed into 100 sections. Compartment used in the functional analysis are shown in gray and light blue. d) Shaded relief of the DEM of 1997, generated from our workflow (Lucas & Gayer, 2022), at the confluence between Mahavel and Rivière des Remparts. e) Same for the year 2003. f) Difference of DEMs between 2003 and 1997 illustrating changes in elevation. Blue areas denote erosion between 1997 and 2003, while red areas indicate sediment accumulation during the same period.
3. Data and Methods

In order to estimate the volumes and the rates at which sediments are transported in the Rivière des Remparts canyon, we calculated differences of Digital Elevation Models of its valley floor at different dates and compared with climatic parameters.

3.1 DEM time series from photogrammetry

DEMbs of the entire drainage area were reconstructed from historical aerial images using photogrammetry (Rupnik et al., 2017). The study area was captured through stereoscopic aerial photos taken by the French Geographic Institute (IGN) during nine campaigns spanning from 1950 to 2011. The time interval between campaigns varies from 5 to 12 years, and the number of images covering the study area ranges from 41 to 174, depending on the photographic equipment and the flight design used in each campaign (Supp. Table 1). In total, we processed 743 images using the dy-achronic shape-from motion workflow following Lucas and Gayer (2022). Nine DEMs of the entire Rivière des Remparts' catchment were generated at a planimetric resolution of 1.25 m (Fig. 1d, 1e). The vertical uncertainties of each DEM range from 0.72 to 2.31 meters (Supp. Table 1.)

3.2 Difference of DEM and geomorphic change

Changes in volume of sediment stored in the river bed between campaign dates were calculated using difference-of-DEM (DoD; Fig. 1f).

For each time interval, the total volume difference was determined by multiplying the DoD with the pixel area and summing it over the entire valley surface. Uncertainties in volume were estimated using the standard deviation (1-sigma) of elevation differences in stable areas, rather than the vertical error of each DEM. Stable areas are defined as areas where no geomorphic change is expected and observed (for every campaign). We selected 17 stable areas covering a total area of 49.5 km$^2$ on the non-incised flanks of Piton de la Fournaise (Supp. Fig. 2). The 1-sigma values, ranged from 2.2 to 5.5 m and were used in the DoD such that any difference in
elevation between DEMs falling within its corresponding ± 1-sigma was ignored (Wheaton et al., 2010; Supp. Table 2). It is important to note that only 4 of the 17 reference areas were unvegetated (Supp. Fig. 2). Consequently, the calculated standard deviations include vegetation growth and therefore, the use of 2-sigmas would greatly overestimate the actual uncertainties on unvegetated areas, including the valley bottom that is of interest in our study. This is demonstrated by the standard deviation within the 4 unvegetated reference areas that range from 1.3 to 3 m. However, as (i) these non-vegetated areas are located only on the upper part and on one side of the basin, and (ii) the 2-sigmas of the non-vegetated areas are consistent with the 1-sigma of the 16 areas, we favored the latter due to their comprehensive coverage around the canyon, extending from the coast to the summit of the volcano (Supp. Fig. 2). This choice allows for better consideration of uncertainties in DEM reconstruction following Lucas and Gayer (2022).

3.3 Sediment transport dynamics and rates

Bed-material transport can be estimated using the so-called morphological approach in which, using the Exner equation (Exner, 1925; Paola & Voller, 2005) and considering the conservation of mass, sediment transport is linked to changes in elevation over time (Antoniazza et al., 2019; Lane et al., 1994). Neglecting lateral transport (Antoniazza et al., 2019; Church, 2006), simplifies the Exner equation (1925) for the one-dimensional case, and averaged sediment transport rates are calculated by dividing the net change in the volume of sediment stored in the entire canyon (\(\Delta V = V_{in} - V_{out}\)) by the period of time (\(\Delta t\)). We calculated the total volume of sediment exported out of the RdR (\(V_{out}\)) and its rate (\(V_{out}/\Delta t\)) over time by estimating the volume of material entering the canyon (\(V_{in}\)), facilitated by our comprehensive coverage of the entire riverbed up to its head.

Additionally, we used the same principle at the reach scale in order to estimate the one-dimensional sediment transport dynamics along the river. One hundred sections extending from the Mahavel scarp downstream to the city of St-Joseph, were manually defined (Fig. 1c). Each section covers an equal area of 50×10^3 m^2 and is oriented perpendicular to the main stream direction. Due to variations of the valley width, the length of the sections ranges from 30 to 1026 m (average length of 146 m), totaling 14 km in length. For each time interval, the net change in
sediment volume within each section \((\Delta V_i < 0 \text{ or } > 0)\) indicating erosion or deposition, respectively) equals the difference between the volume entering the section and the volume exiting it \((\Delta V_i = V_{i_{\text{in}}} - V_{i_{\text{out}}})\). Using the volume of material entering the canyon \((V_{i_{\text{in}}})\), we determined the local sediment inflow \((V_{i_{\text{in}}})\) and outflow \((V_{i_{\text{out}}})\) for each section, enabling the calculation of sediment transport dynamics along the river for each time interval.

Considering riverbed porosity is crucial for establishing a direct link between changes in elevation and the volume of sediment stored in the reach. Previous studies have estimated porosity values ranging between 20% and 35%, for gravel and sands, based on field measurements and empirical and theoretical predictors (Carling & Reader, 1982; Frings, 2011; Seitz et al., 2018; Tabesh et al., 2019). These values align with the vesicularity of the basaltic rocks in the RdR watershed (35% – 45%; Michon et al., 2023), suggesting that, in RdR, the porosity of the lava flows is partly destroyed by the creation of sediments of similar porosity. Porosity can therefore be disregarded in assessing the volume of sediment brought to the river and stored in the reach.

3.4 River flow date estimation

In order to estimate the date at which the ephemeral RdR flows, we trained a machine learning model based on recent satellite image observations and daily rainfall datasets. First, we used a total of 457 Sentinel and 20 Planet images from 2017 to 2023 to manually select dates when morphological changes in the canyon bed were visible, allowing us to infer periods of river flow within the selected timeframe (Supp. Fig. 1). Additionally, daily precipitation data from four rain gauges of the French meteorological agency (Météo-France; Fig. 1a) were used to train a random forest model between 2017 and 2023, linking precipitation intensities to river flow dates. The model incorporates time-delayed daily precipitation data (up to 30 days) to account for the time it may take for precipitation to infiltrate, rise the water table and reach the river, as well as to take into account preconditions favoring translation of precipitation into runoff (such as ground saturation) and the sudden increases in precipitation intensity. The resulting model achieved a good accuracy score of 0.91 ± 0.01. Additionally, in order to predict river flow date from historical precipitation data since 1950, we trained another model with the 2017 to 2023 daily precipitation recorded by the only rain gauge operational between 1950 and 1978 (Grand
Coude; Fig. 1a). The accuracy score for this model is 0.92 ± 0.01. Applying these two models to historical precipitation data, from both the four rain gauge stations between 1978 to 2011 and the Grand Coude station from 1950 to 1978, enabled us to estimate the number of days the river has flowed since 1950.

3.5 Cosmogenic $^3$He concentration in RdR sediments

We measured cosmogenic $^3$He concentrations ($[^3\text{He}]_c$) in olivine samples from two river sands in RdR. The first sediment (MAHA5) was collected on the 1965 deposit at an altitude of 1128 m upstream in the Bras de Mahavel tributary, in the lower part of the gorge section. The second sample (REU13_203) was obtained downstream in RdR at an elevation of 262 m, approximately 6 kilometers away from the outlet (Fig. 1b). For each sample, He concentrations were determined following a standard laboratory procedure (Ferrier et al., 2013; Gayer et al., 2008; Kurz, 1986). Helium isotopic measurements were performed at Institut de physique du globe de Paris using a Nu Noblesse mass spectrometer. The measurements were conducted on handpicked olivine grains with a size range of 1 to 2 mm. The magmatic He ratios were initially measured by crushing ~500 mg of olivine grains under vacuum. Subsequently, the total $^4$He and $^3$He concentrations were measured after melting the resulting powder (Gayer et al., 2008). $^3$He and $^4$He crush blanks were below 1% of the measured signals and furnace blanks were averaging 18% of the sample signals. The radiogenic $^4$He components were derived from ICP-MS measurements of U, Th, and Sm concentrations in the olivine, and the nucleogenic $^3$He components were calculated based on the compositions of major and trace elements in the bedrocks of the watershed (Smietana, 2011). Finally, $[^3\text{He}]_c$ of the two samples were determined by correcting the total $[^3\text{He}]$ for the non-cosmogenic components (Gayer et al., 2008; Kurz, 1986).

4. Results

The accuracy and quality of a reconstructed DEM depend on the amount of information available. Shadows, clouds as well as a limited number of images covering the same area are limiting factors. In the 1950 and 1961 campaigns, clouds in the lower part of the RdR hindered
reliable reconstruction below sections #82 and #95, respectively, while in the three other campaigns of 1978, 1989, and 1997, the scarcity of images (< 3) hindered the reconstruction below sections #97, #98, and #99, respectively. Consequently, to enable the comparison of mass balances and transport rates between different periods, the river was cut at section #96 for all campaigns except for 1950, where it was cut at section #83 (Fig. 1).

4.1 Spatio-temporal evolution of the sediments stored in the canyon bed

The DoD analysis of the entire river bed of each campaign shows that between 1950 and 2011, the RdR canyon bed accumulated a total of 42.3 Mm$^3$ of sediments. This interval witnesses contrasted dynamics over time with five deficit periods during which the sediment loss ranged from -0.2 to -19.6 Mm$^3$ (median value of -0.45 Mm$^3$), counterbalanced by three gain periods, ranging from 7.3 to 48.4 Mm$^3$ (Fig. 2a). These gains and losses reflect the local dynamics of erosion and accumulation along the river, with absolute local gains up to 3 Mm$^3$ and absolute local losses up to -0.8 Mm$^3$ (Fig. 2b).

Figure 2b illustrates the spatio-temporal evolution of the volume of sediment along the river. The DoD analysis shows that during the initial interval from 1950 to 1961, the first half of the canyon bed experienced erosion for ~6.5 km (up to section #57 in blue), while downstream, a fraction of the sediments accumulated (in red), resulting in an overall loss of 0.2 Mm$^3$ (Table 1). Between 1961 and 1966, a significant accumulation occurred due to the Mahavel landslide in 1965 (Michon et al., 2023). The debris pile is visible for 4 km (up to section #44, in red on Fig. 2b) representing a volume of 44.9 Mm$^3$. Downstream, the canyon bed experienced slight erosion compared to its state in 1961 (sections #44-57), followed by another sediment pile totaling 2.4 Mm$^3$ (sections #58-67), and a slight accumulation at the end of the canyon. The next period, from 1966 to 1978, is marked by a new accumulation of 5.2 Mm$^3$ over 2 km in the upper reach, followed by areas of erosion (sections #20-35), deposition (sections #36-57), and erosion (sections #58-95), contrasting with the areas of erosion, and deposition of the previous profile. Between 1978 and 1984, no sediment contribution occurred in the upper reach. Nonetheless, the previous alternating pattern of erosion and deposition persisted, albeit with lower intensity and slightly shifted downstream. Between 1984 and 1989, a new input of 1.2 Mm$^3$ occurred over the first 2 km of the canyon. Downstream, the previous alternating pattern of erosion and deposition...
is less pronounced, although still discernible. Then, another period of substantial accumulation occurred between 1989 and 1997, resulting in an overall gain of 8.6 Mm$^3$. The majority of this accumulation is visible over the first 2 km of the canyon, accounting for 7 Mm$^3$. Downstream, a new pattern of erosion and deposition seems, this time, to contrast with that of the previous profile. Between 1997 and 2003, the first kilometer of the canyon is marked by erosion while the rest of the canyon shows mostly deposits, which are important between the first and fourth kilometer and then become more timid, except at the end of the canyon. Finally, the interval between 2003 and 2011 shows a major loss of 19.6 Mm$^3$, spanning from section #0 to section #95, suggesting no contribution before section #0.

Overall, the comparison of sediment volumes stored in the river between periods indicates a clear downstream migration of material, characterized by erosion of deposits and deposition in eroded areas. Furthermore, it highlights significant contributions originating from the Mahavel headwall, primarily concentrated within the first 2 km of the canyon, except for the major landslide of 1965.
Figure 2. Spatio-temporal evolution of the sediments stored in the canyon bed. a) Total volume of sediment gained and lost between consecutive years in the entire canyon, in millions of cubic meters. Black half-circles indicate deficit of sediment between two consecutive years (the most recent minus the oldest), while empty circles denote accumulation of sediment. b) Volume of sediment gained (aggradation in red) or lost (erosion in blue) between two consecutive years, shown for each section along the canyon. The black lines represent the local (section-to-section) dynamics of sediment transport. A black point indicates the section where the volume transfer becomes negative downstream. The black dashed line for the period 1961-1966 represents the section-to-section transfer profile when using a contribution of 59.7 Mm$^3$ (Michon et al., 2023).
4.2 Estimating the contribution to the river

As outlined previously and based on the negative volume changes observed in the initial sections of the canyon (Fig. 2b), no sediment input occurred during the periods of 1950-1961, 1978-1984, and 2003-2011. By contrast, positive volume changes observed in the first 2 km of the canyon during the remaining five periods suggest contributions from upstream section #0, in good agreement with the dates of the well-known events reported in 1965, 1995 and 2001 (Michon et al., 2023). By summing the volume of each section showing consecutive positive net changes over the initial kilometers (highlighted in red in Fig. 2b), we estimated contributions ranging from 1.2 to 44.9 Mm³ (Table 1) for the periods 1961-1966, 1966-1978, 1984-1989, 1989-1997, and 1997-2003.

Lateral collapses or slumps occurring on the canyon walls could also bring sediments to the river. While no major collapses have been recorded on the lateral canyon walls, aerial images have revealed numerous shallow landslide scars over the 62-year study period. However, these scars have had limited reach to the river bed. To evaluate the significance of these lateral contributions, we conducted field measurements after cyclone Belal struck La Réunion between January 13th and 16th, 2024. Out of twenty-four shallow landslides triggered by the cyclone in the RdR, only six reached the river bed. These deposits, between ~3 m and ~5 m in height, contributed a total of only 0.03 Mm³ to the river, suggesting that such lateral contributions are negligible (2-3 orders of magnitude lower) compared to the overall evolution of sediment volume in the canyon bed. Moreover, their limited height, falling within our 1-sigma error, excludes them from our DoD calculations.
Table 1. Summary of volume balance in RdR canyon: $V_{in}^{DoD}$: Volume contributed to the RdR, estimated from the DoD (see text for detail). $\Delta V^{DoD}$: Volume difference between two consecutive years. $V_{out}^{DoD}$: Volume exported out of the watershed ($V_{in}^{DoD} - \Delta V^{DoD}$). $V_{in}^*$, $\Delta V^*$, $V_{out}^*$: Volume corrected for re-evaluation of contribution and extraction (see main text for details).
4.3 Exported volumes and transfer rates

Using the previously estimated values for both the total sediment stored in the canyon bed ($\Delta V$) and the sediment entering it ($V_{in}$), we calculated the volume of sediment exported out of the canyon ($V_{out} = V_{in} - \Delta V$). The exported volumes range from 0.2 to 19.6 Mm$^3$ for the periods 1961-1950, 1966-1978, 1978-1984, 1984-1989 and 2003-2011. Dividing this by the time period ($\Delta V/\Delta t$), we calculate export rates from 0.02 to 2.42 Mm$^3$/yr. However, for the remaining three periods, export volumes appeared negative, suggesting a discrepancy either in the estimate of the volume of sediment stored ($\Delta V$) or in the volume entering the canyon ($V_{in}$). This is demonstrated, for the period 1961-1966, by the discrepancy between our estimated contribution of 44.9 Mm$^3$ and the volume of 59.7 ± 3.1 Mm$^3$ of collapsed material calculated by Michon et al. (2003) for the major landslide of 1965. Using this value, the exported volume for this period becomes 11.3 Mm$^3$ at a rate of 11.3 Mm$^3$/yr as the landslide occurred one year before the end of the period (Table. 1).

The spatio-temporal evolution of sediment transfer can be further described by considering section-to-section material transfer ($V_{i-out}=V_{i-in}-\Delta V_i$), where the volume of material leaving one section becomes the volume entering the next, propagating the volume that entered the canyon in the first section. The local downstream sediment transfer along the river, illustrated by the black arrows in figure 2b for each time interval, conforms to anticipated patterns. Section-to-section transfer increases in eroded areas and decreases in deposition areas, reaching maximum and minimum values at the transition points between erosion and deposition, and deposition and erosion, respectively. For the period 1950-1961, with no contribution to section #0, sediment transfer gradually increases, reaching a maximum section-to-section transfer of 4.96 Mm$^3$ (corresponding to an averaged transfer rate of 0.45 Mm$^3$/yr) at the transition from erosion to deposition (~6.5 km). In contrast, the period 1961-1966 shows a different trend. Initially, our estimated contribution of 44.9 Mm$^3$ results in a negative local transfer after 4 km, indicating an implausible upstream transfer of sediment (black point, Fig. 2b). However, considering the volume that collapsed in 1965 as calculated by Michon et al. (2023), the profile shows a rapid decrease to 14.8 Mm$^3$ after 3 km, followed by a slighter decrease to 11.3 Mm$^3$ towards the mouth of the river (dashed line, Fig. 2b). The subsequent three periods, 1966-1978, 1978-1982, and
1984-1989, show remarkably consistent profiles, illustrating the downstream dispersion of
sediment. The maximum section-to-section transfer rate in the first half of the canyon increased
from 0.46 Mm$^3$/yr for 1966-1978 to 0.72 Mm$^3$/yr for 1978-1982 before decreasing to 0.22
Mm$^3$/yr in 1984-1989. Importantly, when using our sediment contribution estimates for section
#0, minimum values consistently remain positive or equal zero at certain sections. This
underscores that sediment primarily traversed specific sections during these intervals, and
highlights the precision of our estimates. For the next period, 1989-1997, section-to-section
transfer results in a negative anomaly at 2 km, while for the period 1997-2003, the negative
anomaly emerges close to the mouth of the canyon (black points, Fig. 2b). Finally, for the period
2003-2011, with zero contribution to section #0, the section-to-section transfer gradually
increases along the canyon, reaching an average maximum of 2.46 Mm$^3$/yr at its mouth.

4.4 Cosmogenic isotopes and sediment source tracking

[$^3$He]$_c$ of the upstream sample (MAH5) and the downstream sample (REU13_203) are 1.50 ±
0.08 × 10$^6$ and 0.85 ± 0.05 × 10$^6$ at/g, respectively. MAH5 was collected from the upper section
to determine the cosmogenic signature of collapsed material. Its [$^3$He]$_c$ is one order of magnitude
lower than the deepest sample obtained from a drill core in the Plaine de
Remparts (1.24 × 10$^7$ ± 1.08 × 10$^6$; Sarda et al., 1993), the plateau overlooking Mahavel, which collapsed in 1965
(Michon et al., 2023). This difference aligns with the expectation that the deposit comprises a
mixture of material long exposed to cosmic rays (~60 kyrs), and material shielded but more
abundant given the shape of the collapsed scale (900 m deep, 650 m long and 150 m wide;
Michon et al., 2023). The downstream sample, REU13_203, shows a surprisingly similar [$^3$He]$_c$
concentration, with only a factor of ~1.8 difference. Using this cosmogenic concentration in a
traditional manner would imply a long-term erosion rate of 0.15 ± 0.01 mm/yr (0.41 ± 0.04
Kt/Km$^2$/yr), which starkly contradicts the long-term erosion rate of 4.8 mm/yr estimated from
surface reconstruction (14 Kt/Km$^2$/yr; Gayer et al., 2019), and the morphology of the canyon
itself. Instead, the close cosmogenic $^3$He signature shared between the deposit material and the
downstream river sediment implies that the majority of the sediment in the river originates from
the 1965, 1995 and 2001 deposits. This indicates that inflows from the upper part of RdR and
lateral inputs from Bras Dimitile or shallow landslides have negligible contributions compared to the efficiency of the river in draining the main landslides deposits.

5. Discussion

5.1 Reassessment of the contribution of rock avalanches

The three periods showing implausible negative export volumes are the periods including the three major landslides in 1965, 1995 and 2001. For periods 1961-1966, 1989-1997, and 1997-2003, contributions estimated from the river bed DoDs consistently fall short, leading to implausibly upstream sediment transfer (Fig. 2b) and suggesting that the actual contributions are likely higher. Specifically, for 1961-1966, the volume of the 1965 collapse (59.7 ± 3.1 Mm$^3$ in Michon et al. (2023), revised to 59.7 Mm$^3$ using the error correction method described in section 3.2) leads to a positive downstream sediment transfer profile (dashed line, Fig. 2b). However, the inconsistency between the volume of the deposit (44.9 Mm$^3$) and the total volume of the collapse (59.7 Mm$^3$) raises questions. To explain these differences, Michon et al. (2023) hypothesized material storage in the gorge upstream of section #0 but lacked confirmation in the absence of more recent DoDs. This hypothesis now gains support from the analysis of the subsequent 1966-1978 period, which shows a contribution of 5.2 Mm$^3$ despite no recorded collapses. This confirms that material from the 1965 collapse was stored and then later flushed from the gorge section. Therefore, we recalculated the contribution for the 1965 event to be 54.5 Mm$^3$, resulting in an updated downstream sediment transfer profile (red line, Fig. 3b) and a revised overall output of 6.1 Mm$^3$.

Extending the DEM reconstruction timeline to 2011 enabled us to estimate the volume of collapsed material for the 1995 and 2001 events. Following Michon et al. (2023), the analysis of the DoD for the valley wall between 1989 and 1997, as well as between 1997 and 2003, revealed horizontal cliff retreats of ~ 70 m over a width of 480 m and 150 m over 750 m, respectively. Despite this difference in horizontal extent, the events of 1995 and 2001 contributed volumes of 8 Mm$^3$ and 14.3 Mm$^3$ to the river, compared to the previous 7 and 6.9 Mm$^3$, respectively, when only considering the initial sections (Table 1).
Despite such reevaluation, for the period 1989-1997, section-to-section transfer still showed negative value close to the mouth of the canyon, and an additional 0.5 Mm$^3$ is required to achieve a positive transfer profile with a resulting net output of 0 Mm$^3$. It is unlikely that this necessary surplus of 0.5 Mm$^3$ is associated with lateral contributions from shallow landslides, as we did not observe an exceptionally high number of scars in the aerial images. However, a minor underestimation in the uncertainty calculations for the DoD could potentially account for the discrepancy. Nevertheless, such potential misestimations—whether from uncertainties or lateral contributions—are only relevant for periods where the overall output is close to zero, as appears to be the case for this 1989-1997 period. In fact, the sediment transfer profiles for the periods 1966-1978, 1978-1984, and 1984-1989 are remarkably well-balanced, with some transfers at zero but consistently avoiding negative values (Fig. 2b). This implies generally accurate uncertainty estimates and insignificant lateral contributions. Consequently, we have revised the upstream contribution for 1989-1997 to 8.6 Mm$^3$, resulting in a balanced net output of zero.

Finally, for the period 1997-2003, the contribution of 14.3 Mm$^3$ from the 2001 event results in a positive sediment transfer profile, leading to an overall output of 7 Mm$^3$. Given that no additional contribution is evidenced in the subsequent 2003-2011 period, we suggest that no sediments were significantly stored in the gorge section during the 2001 event.

5.2 Accounting for industrial extraction

In the downstream part of the river, special attention is required for sections ~#90 to #95, where sediment extraction by a private company began in the mid-1980s (from section ~#90 to ~#100). Although precise extraction volumes and locations are difficult to determine, company reports suggest that around 0.95 Mm$^3$ was extracted during the 1984-1989 period. This volume aligns with the negative volume change observed from section #87 to section #95 during the same period (Fig. 2b), which totals 0.99 Mm$^3$. However, it does not definitively prove that all the erosion was due to human extraction, considering that extraction also took place downstream from section #95 to section ~#100. Therefore, by incorporating only half of this reported extraction volume into the global canyon bed sediment budget, the overall exported volume for 1984-1989 is adjusted to 0.95 Mm$^3$. For the subsequent periods, extraction impact is not evident in the volume change profiles of the river's lower sections. To the contrary, these sections
indicate sediment accumulation during the 1989-1997 and 1997-2003 periods, and a pronounced decrease in erosion for 2003-2011. Nonetheless, when projecting a yearly average extraction volume, equivalent to that of the 1984-1989 period (only based on sparse reports), the recalculated overall outputs for 1989-1997, 1997-2003, and 2003-2011 are -0.6 Mm³, 6.5 Mm³, and 18.9 Mm³, respectively. Such corrections are negligible for 1997-2003, and 2003-2011. However, for 1989-1997, considering the uncertainties regarding the exact extent and locations of the areas of extraction and therefore the accuracy of the correction, we suggest keeping a contribution of 8.6 Mm³ and an overall output of 0 Mm³ instead of -0.6 Mm³ (Table 1; Fig. 3).
Figure 3. Volume balance in RdR canyon. a) Volume of sediment contributed to the river for each period ($V_{in}^*$ in Table 1). The three rockfall pictograms indicate the periods of the three major landslides. b) In green, the difference in volume between each year and 1950 is shown for each compartment along the canyon. Red lines represent section-to-section sediment transfer, derived from the difference in volume between consecutive years. c) Volume of sediment exported by the river for each period ($V_{out}^*$ in Table 1). d) Annual export rates for each period ($\Delta V^*$ in Table 1). e) Number of cyclones, tropical storms or storms during each period. For the period 1950-1961, no cyclone was officially reported (and named).
5.3 Functional division of canyon bed dynamics

Differences of DEMs (Fig. 2b and 3b) illustrate how the river drained the sediments supplied from Mahavel’s cliff collapses between 1950 and 2011. Sediments mainly stored in the upper reaches were gradually dispersed downstream over the 62-year period. Transport processes have been reported as probably hyperconcentrated flows and bedload transport of coarse material (boulder up to ~1-2m diameter), pebbles, gravel and fine particles (Garcin et al., 2005). In detail, the dynamics of transport in the canyon bed exhibits a step-like evolution due to both its morphology (sinuosity and slope changes over time) and the intermittent supply of sediments. Differences of DEMs, using 1950 as reference (Fig. 3b), helped identify seven compartments, each with distinct evolutionary patterns. The first compartment C1 (section #0-18) corresponds to an accumulation zone, subject to occasional local incision but predominantly buried under debris from every cliff collapse. Downstream, the second compartment C2 (section #19-36) is an active transition zone where torrential processes incise its upstream part, and its downstream part with some aggradation in between. The transitional nature of this section is evident from its diminishing volume over time, with gain only from major landslides (Fig. 3b). The remaining five compartments correspond to straighter sections and narrower segments. Compartment C3 (section #37-53) accumulates products from the incision of the upstream compartment C2 (Fig. 3b), while the narrower compartment C4 (section #54-57) exhibits limited aggradation. This indicates an efficient transport capacity attributed to the high discharge resulting from the narrow gorge shape of the canyon at the location. The remaining compartments (C5-section #58-68, C6-section #69-83 and C7-section #84-96) exhibit step-like patterns of aggradation and erosion (Fig. 2b and 3b). As the drainage area increases, the rise of discharge in these compartments promote sediment transit towards the ocean.

Although the analysis of temporal evolution of profiles since 1950 might initially suggest the presence of two distinct transit regimes on either side of C4 (Fig. 3b), it actually clearly demonstrates the widespread dispersion of sediments through river transport.

5.4 Efficiency of extreme precipitation in sediment transport
The Rivière des Remparts is an ephemeral river that flows only during storm events, as reported by witnesses, for an average of 5 to 7 days per year. Considering such a rate, 39.6 Mm³ of sediment were then evacuated in 310 to 434 days in 62 years, resulting in an extraordinary flux of 0.09 to 0.13 Mm³/day.

Although twenty-five storms, tropical storms, and cyclones events, most likely to trigger flow in the RdR, have been recorded over La Réunion since the 1960s, the analysis of this activity by period reveals no clear correlation with export volumes or rates (Fig. 3e). For example, the decline in exported material from 5.7 to 1.3 Mm³ between 1966-1978 and 1978-1984, respectively, corresponds to a reduction in cyclone occurrences from 5 to 2 during these periods (Fig. 3e). In contrast, the period between 1984 and 1989 saw only 0.95 Mm³ exported despite the presence of 3 cyclones and 2 tropical storms (Fig. 3e), underscoring the challenge of reconciling step-like processes averaged over several years with the daily-scale nature of extreme precipitation events.

Yet, in order to better assess the efficiency of extreme precipitation in sediment transport, we estimated the river date flow from a random forest model based on the observation of geomorphic change in the river bed (from satellite images, cf. methods). Using the historical record of daily precipitation, we then estimated modeled river flow dates since 1950. It is important to note that these estimates represent the maximum number of days, as Sentinel and Planet satellite images are not available daily. Furthermore, observations of the river during precipitation events are obstructed by cloud cover. The dating of changes in the river bed was contingent upon the availability of images, potentially leading to a slight overestimation of the actual duration of flooding events. Despite uncertainties regarding the precise dates of flooding in the training set, we predict an average of 6.3 flood days per year between 1950 and 2011. This estimate agrees with witness observations, and therefore suggests that 39.6 Mm³ of sediment were evacuated over 391 days in total, corresponding to an average flux of 0.1 Mm³/day.

In greater detail, the modeled flood dates align well with occurrences of major climatic events classified by Météo-France as storms, tropical storms, and cyclones since 1961 (Fig. 3e). The model accurately identifies twenty out of twenty-five events, indicating the river's rapid response to intense rainfall events. However, it is important to note that the model may not capture every event, as cyclone trajectories often result in varying impacts across the island. Additionally, flow dates may slightly follow the official period of extreme events while still
being related to them. Nonetheless, other floods are predicted outside the major cyclone dates, suggesting that other storms or specific weather conditions, not officially reported by Météo-France, can induce flooding.

In order to distinguish the types of rainfall events that result in runoff, we computed the distribution of the annual percentile rank of precipitation on each flow day. For each year, we calculated the percentile rank of each daily rainfall intensity at each of the 4 rain gauge stations (Fig. 1a). Then we selected the values at each day of runoff. The distribution of the percentile ranks (Fig. 4) shows that at least half of the flow days occur when precipitation percentile ranks are greater than or equal to 87%, while 25% of the flow days occur for percentile ranks greater than or equal to 99%, respectively. This confirms a rapid translation of intense rainfall into runoff in the RdR. Nonetheless, the distribution also indicates that a portion of the river flow is related to lower percentile ranks centered around 20%. This can be attributed to the gradual decrease in river discharge after a rainfall event, even if the rain has ceased or remains minimal. Additionally, the slow rise of the water table due to consistent but low precipitation over a certain period may enable low-intensity rainfall to trigger river flows. Finally, it is important to note that some days of flow with low rainfall intensities may also result from the overestimation of the river flow period when manually inspecting geomorphic changes in the riverbed on satellite images not available daily.

With the high median and high third quartile of yearly rainfall percentile ranks (Fig. 4), we anticipate that river flows are triggered by intense and rare precipitation events at the yearly scale. We propose that sediment is exported from the river at an estimated rate of 0.1 Mm³ per day of rainfall, primarily associated with rainfall intensities greater than 99% of the annual rainfall intensities (Fig. 4).
Figure 4. Distribution of the annual percentile ranks of precipitation at each flow date. For each year, we computed the percentile rank of each daily precipitation intensity measured at the rain gauge stations (annual percentile ranks). Blue circles represent the annual percentile ranks on the dates when the model predicts river flow, for each rain gauge station. Red arrows indicate the date of the extreme events officially recorded as such by Météo-France. Red circles represent the annual percentile ranks of the rainfall intensity on dates recorded as extreme events by Météo-France. (BP) Marginal box plot presenting the quartiles of all the annual percentile ranks over the 62 years. (BP) Marginal distribution of the percentile ranks showing that the majority of the flow dates responsible for sediment transport corresponds to high-percentile precipitation intensities.
5.5 Erosional efficiency of extreme precipitation and consequences on source to sink

The erosive potential of extreme precipitation events extends beyond their ability to initiate landslides as they amplify riverine transport capabilities through augmented discharge. The intense erosion of Réunion Island has been well-established, evidenced by high chemical weathering rates (Louvat & Allègre, 1997) and long-term erosion rates surpassing those observed in certain active mountain ranges (Gayer et al., 2019). By extrapolating the RdR export rate of 0.1 Mm$^3$ per day of rainfall (equivalent to 0.64 Mm$^3$/yr) since the last filling of the watershed by Piton de la Fournaise activity (63±3 kyr ago; Gayer et al., 2019), we derive a long-term average erosion rate of 25.9 kt/km$^2$/yr. This erosion rate is nearly twice the value of 13.5±2.8 kt/km$^2$/yr estimated from surface reconstruction (Gayer et al., 2019). However, this disparity is not surprising, as mass wasting, particularly significant landslides, can only occur when the river has incised the volcano deeply enough to facilitate slope destabilization. Therefore, high erosion rates, resulting from frequent and/or large landslides and efficient sediment transport, would only begin after a certain period in the life cycle of a volcanic watershed. This seems to be corroborated, in the RdR, by the fact that the deep-sea fan of St-Joseph (offshore RdR) shows intrusions of fine sands (coarser elements in the sediment core) approximately 45 kyr ago, followed by an increase in both the frequency and thickness of such deposits since then (Sisavath et al., 2012).

Studies on the extensive submarine structures around Réunion Island have indicated a highly effective transfer of sediment from land to sea. This efficiency is facilitated by the absence of a coastal platform, enabling a continuous transition from fluvial flows to submarine gravity processes and flows (Babonneau et al., 2013; Mazuel et al., 2016; Saint-Ange et al., 2013). These processes include sediment-rich turbiditic currents initiated by gravity-driven flows of granular sediments, forming deep-sea fans (Babonneau et al., 2013; Mazuel et al., 2016; Saint-Ange et al., 2013). Consequently, we anticipate that the observed increase over time in the frequency of coarse deposits in the sediment core of the deep-sea fan of St-Joseph since ~45 kyr reflects a rise in on-land erosion. This increase could particularly be associated with mass wasting processes.
and efficient sediment transport, which, in turn, could be linked to an increase in the frequency
and/or intensity of extreme precipitation events since 45 kyr.

Finally, while catastrophic landslides and debris flows can occur rapidly, within minutes
(e.g., Michon et al., 2023), the mobilization of coarse sediment in the river is often viewed as a
more prolonged process (Croissant et al., 2017). Our study reveals that the evacuation of a
significant amount of landslide debris occurs over a span of days in settings subjected to intense
precipitation. Here, we documented river flows containing over a hundred thousand cubic meters
of sediment, encompassing particles up to 2 meters in diameter, transported within a 24-hour
timeframe. Coupled with highly efficient transfer of sediment from land to sea facilitated by the
absence of a coastal platform (Saint-Ange et al., 2011) this study reveals an extraordinarily rapid
conveyance of material from slopes to deep-sea fans. Extrapolated to the entire island, we
expect that such a rapid transfer of solid particles from mass wasting processes to offshore
sedimentary systems will enhance CO$_2$ consumption by transporting and burying organic matter
particles. Although there is currently no available data on particulate organic carbon (POC)
export of the river around Réunion, the combination of abundant tropical vegetation and the
frequent occurrence of landslides in Réunion suggests that the transport and burial of POC
should significantly contribute to the island's already high efficiency in CO$_2$ consumption.

6. Conclusion

Time series DEM derived from shape-from-motion technique, using historical aerial images over
the watershed of Rivière des Remparts, allowed us to assess sediment transfer dynamics from
1950 to 2011. Our results reveal that three major landslides or rock avalanches contributed 82.6
Mm$^3$ to the upstream part of the RdR canyon, out of a total of 83.7 Mm$^3$. Over 62 years, the
ephemeral but efficient flooding of the river removed 39.6 Mm$^3$ (48%) from the watershed at an
average rate of 0.64 Mm$^3$/yr. Section-section analysis along the river reveals a clear downstream
spreading of sediment over time, confirmed by the cosmogenic $^3$He sediment source tracking.
Additionally, geomorphic analysis divides the canyon into distinct zones of aggradation,
incision, and transit toward the mouth of the watershed. The flow date model of the ephemeral
river reveals that the total transfer of 39.6 Mm$^3$ actually occurred during 391 days, with an
extraordinary export rate of 0.1 Mm$^3$/day. Flow dates align well with dates of well-known and
officially reported cyclones and tropical storms. However, our investigation demonstrates that sediment transfer also occurred outside of these periods. Analysis of rainfall intensities during flow dates highlight that transport is indeed concentrated during intense rainfall periods. This illustrates the effectiveness of intense precipitation as the main factor for evacuating sediments and eroding watersheds. Finally, the modern erosion rate estimated for the period 1950-2011 exceeds the long-term rate by a factor of two, emphasizing watershed erosion rate evolution over time. In the light of these results, and in the context of global change, we anticipate a significant increase in the extreme event contribution to the continental surface dynamics.

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Data Availability Statement

Archive aerial photographs of the Institut Géographique National (IGN) are available for free at https://remonterletemps.ign.fr/. DEMs have been built from the IGN images with the approach described in Lucas and Gayer (2022). Meteorological data of Météo-France are available at https://publitheque.meteo.fr/.

References


