Technical Note

Landslides
DOI 10.1007/s10346-024-02361-2
Received: 31 January 2024
Accepted: 23 August 2024

Raphaël Kerverdo · Sara Lafuerza · Christian Gorini · Alain Rabaute · Didier Granjeon · Rémy Deschamps · Eric Fouache · Mina Jafari · Pierre-Yves Lagrée

The impact of Storm Alex on the Vievola catchment: a quantitative analysis of sediment volume and morphological changes in the Roya River tributaries

Abstract This study investigates the sediment dynamics resulting from the extreme Storm Alex in October 2020 in the Roya Valley and its tributaries in the Alpes-Maritimes region, France. The storm, triggered by a low-pressure system, led to unprecedented rainfall, causing extensive flooding and erosion in the region. Despite limited pre-flood data, the study employs aerial and satellite imagery, digital elevation models, and field surveys to quantify sediment mobilization and its effects on the Viévola alluvial fan in the Roya Valley. The Roya Valley's complex geomorphology, characterized by steep gradients, gullies, and torrential streams, played a significant role in sediment transport. The study reveals that the Dente and Rabay torrents were major sediment contributors, with gullies in these areas producing substantial erosion. Bank erosion in the Dente valley was particularly prominent, attributed to geological factors and glacial deposits. The analysis, relying on topographical comparisons and digital data, assesses sediment volumes eroded and deposited during the event. Despite challenges in data quality, the study offers valuable insights into sediment dynamics during extreme hydro-sedimentary events. The Viévola catchment area is a focal point, emphasizing the importance of scree and fluvio-glacial deposits as primary sources of sediment. The findings emphasize the need for improved pre-event data and monitoring in mountainous regions susceptible to extreme events. The study's methodology, despite limitations, contributes to a better understanding of geomorphic responses to extreme events. Expanding similar studies to cover a wider range of catchment areas and incorporating field data offers potential for enhanced hazard assessment and management strategies. The research underscores the critical role of sediment transport in shaping landscapes and impacting human infrastructure during extreme flood events.

Keywords Storm Alex · Torrent · Flood · Erosion · DoD · GIS

Introduction

The high valleys of the Tinée, Vésubie, and Roya Rivers were struck by the extreme Storm Alex from mid-day on October 2, 2020, to the early morning of October 3rd. This storm was triggered by the rapid deepening of a low-pressure system over the Atlantic. The Alex storm reached the west coast of France the night of October 1st, generating a significant southern flux coming from the Mediterranean Sea. The warm and humid air mass from the Mediterranean Sea caused an exceptional Mediterranean rainfall episode in the Alpes-Maritimes hinterland (Fig. 1), exceeding the 100-year return period rainfall for a 4-h total and a 1000-year return period rainfall for a 12-h total (Carrega and Michelot 2021; Cerema 2021; ONF-RTM, ONF-DRN and INRAE-ETNA 2023). In the Roya Valley, the maximum cumulated rainfall in 24 h was observed at Mesches dam at about 663 mm (Cerema 2021).

Hydrological modelling of the Alex Storm, calibrated on the few available field observations, made it possible to estimate the peak discharge of the Roya River between 1100 and 1800 m^3/s at Breil-sur-Roya (Cerema 2021). These changes are detailed in Table 1, providing a clear picture of the impact of the storm on the valley based on the work of Liébault et al. (2024).

Our work presents the methodology for quantifying the mobilized sediment during the Storm Alex in one of the most active tributary systems of the Roya Valley, namely the Viévola alluvial fan (Figs. 1 and 2), and discusses the impact of the data availability on quantifying erosion and sediment transport for hazard assessment. The flatter landforms developed in alluvial fans, such as the Viévola fan elevated above the Roya floodplain, are attractive for site developments, such as camp resorts (Fig. 2A). The activity recorded in the Viévola alluvial fan highlights how these sedimentary systems can severely impact human activity during extreme floods (Fig. 2B).

Study area

The Roya subalpine valley (Fig. 1) encompasses a watershed of 671 km² bordered in the North by the Argentera-Mercantour massif (elevations up to 3000 m) and the Col de Tende (1889 a.s.l). The Roya River extends 60 km in a north to south direction, flowing into the Mediterranean Sea. Its valley exhibits a V-shaped forming significant gorges that channel the river for much of its course (Blanchard 1949; Julian 1980). The average valley gradient is about 56% (ONF-RTM, ONF-DRN and INRAE-ETNA 2023). Its morphology characterized by a step-pool channel is primarily fed by gullies and torrents that incise the valley slopes. The lithology of the region, mainly comprising competent rocks such as a Jurassic/Cretaceous marls and limestones, contributes to these morphologies. Alluvial terraces and fans mobilizing fluvio-glacial materials are found as the valley widens, notably at the Viévola alluvial fan (Fig. 2) at the confluence of the Morte and Roya Rivers, and at Saint-Dalmas-de-Tende at the confluence of the Bieugne and Roya Rivers. The Bieugne River flows downstream the Mesches dam, where the highest rainfall was recorded (Fig. 2).

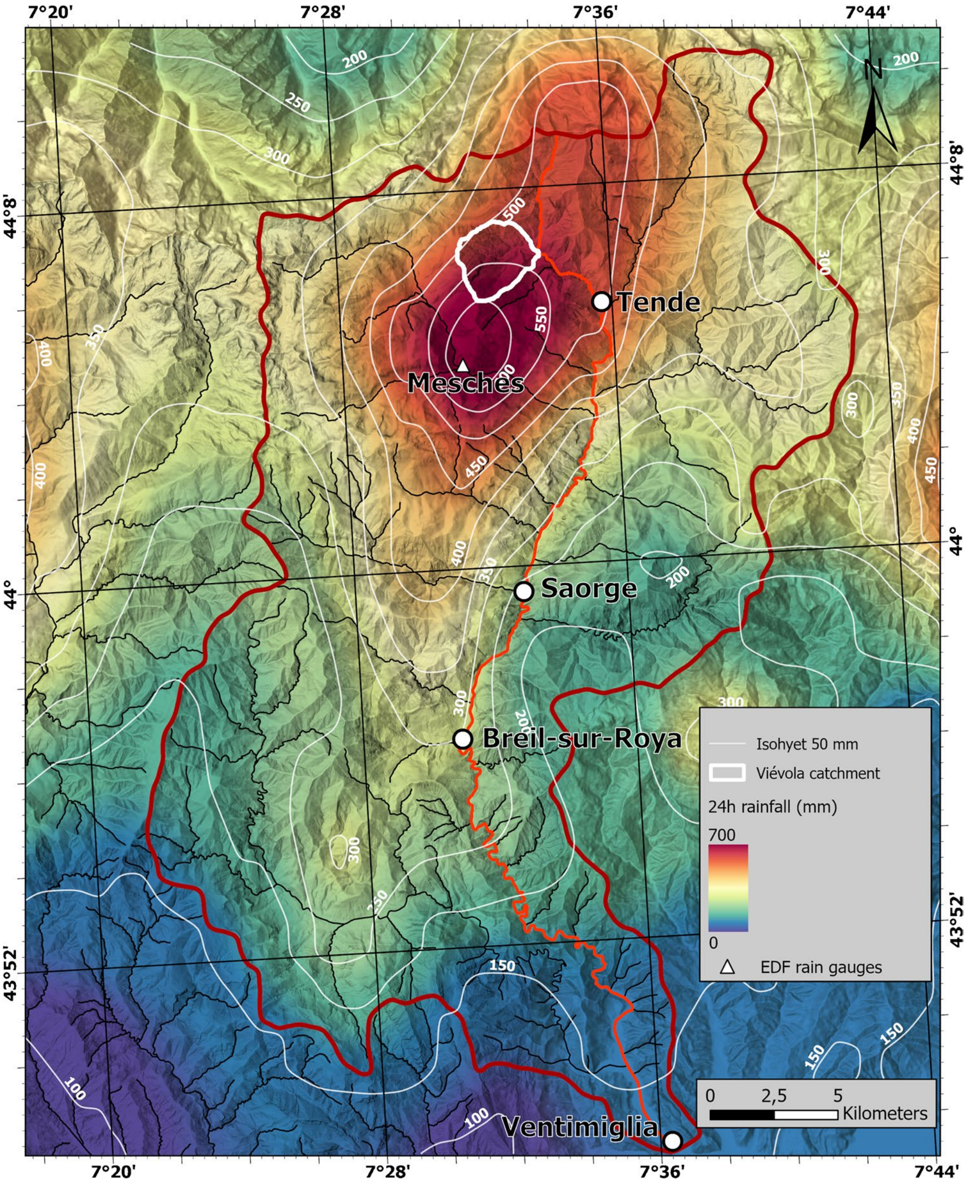

Fig. 1 Twenty-four-hour rainfall map in the Roya Valley, as modified by Liébault et al. (2024). The catchment divide is highlighted in red, stream networks are depicted as thin black lines, and the Roya River is represented by a thick dark orange line. The Vievola catchment area is delineated in the upper part of the valley in light white

The Viévola fan covering an area of 6.5 km² evolves where the Morte and Dente torrents deconfine and flow into the right bank of the Roya River (Fig. 2). The morphology of this watershed (Fig. 3A) has a radial shape sculpted by the last glaciation (Julian 1997; Brisset et al. 2015). This area is divided into five valleys: the Dente, Rabay, Morte, Para, and Scabrie Valleys (Fig. 2). The Dente torrent with a length of 1.8 km converges with the Morte torrent at the apex of the Viévola alluvial fan. The Rabay torrent, 1.4 km long, serves as a tributary to the Dente torrent. The longest of these is the Morte, stretching 2.5 km. The Para and Scabrie torrents feed into the Morte, each 1.4 km and 1.1 km long respectively. Torrent gradients exceed 30°. The unconsolidated rocks within the Roya catchment primarily comprise scree slopes and aprons located on the slopes of different torrents, as shown in Fig. 3A. Notably, the downstream segments of the Dente and Morte torrents are characterized by glacial outwash deposits (ONF-RTM, ONF-DRN and INRAE-ETNA 2023).

Data

A range of data sets including aerial and infrared pictures and digital elevation models covers the pre-flood and post-flood periods. Following Alex flood, the IGN (Institut Géographique National, French geographical survey) conducted an emergency survey with aerial orthoimages and LiDAR images covering the major river floors of the Tinée, Vésubie, and Roya Valleys (IGN 2020). The post-Alex LIDAR 2020 has a planimetric resolution

Table 1 Summary of morphological changes and mobilized volumes for the Roya and Vésubie catchments as reported by Liébault et al. (2024). The volumes were calculated using LiDAR data obtained by the Nice metropolitan authority in 2018. In the case of the Roya Valley, the unavailability of pre-flood LiDAR data hindered the determination of mobilized volumes. IC, Index of Confinement, which is defined as the ratio between the post-active channel band and modern valley floor width

Vésubie							
Surface channel (ha)		Modern valley floor (ha)		Mean active channel (m)		IC (ratio)	
Before (2017)	After (2020)	Before (2018)	After (2020)	Before (2018)	After (2020)	76%	
68	274	317	363	19	79		
Total erosion		Total deposition		Tributaries input		Net budget exported	
Value	Uncertainties	Value	Uncertainties	Value	Uncertainties	Value	Uncertainties
4.13 Mm^3	0.011 Mm^3	3.49 Mm^3	0.016 Mm^3	1.51 Mm^3	0.025 Mm^3	2.06 Mm^3	0.050 Mm^3
Roya							
Surface channel (ha)		Modern valley floor (ha)		Mean active channel (m)		IC (ratio)	
Before (2017)	After (2020)	Before	After (2020)	Before (2017)	After (2020)	75%	
59	137	Unknown	181	15	37		
Total erosion		Total deposition		Tributaries input		Net budget exported	
Unknown		Unknown		Unknown		Unknown	

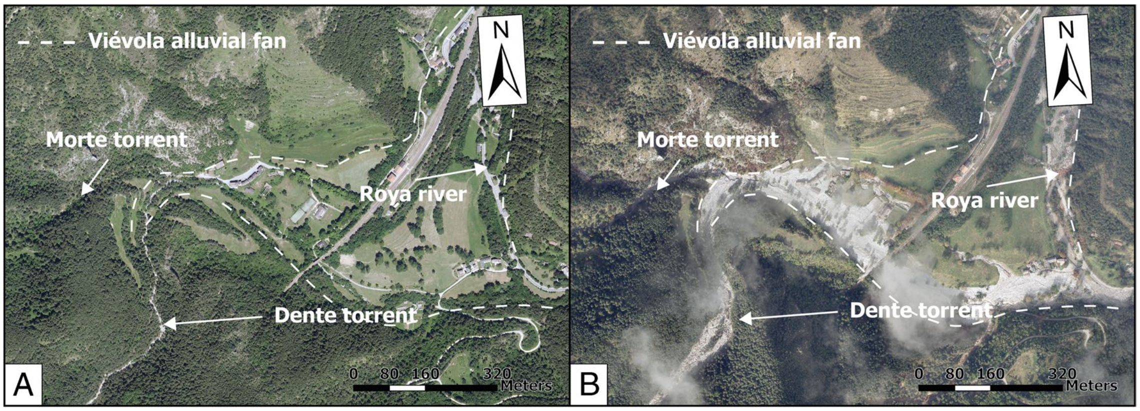

Fig. 2 The Viévola resort camp is depicted in two snapshots, showcasing the conditions before and after the October 2020 flood. In the post-flood image, the torrents and the Roya River on the right side of the picture exhibit significant changes, with noticeable increases in depth and width. The southern part of the Viévola alluvial fan was heavily embanked following the flood

of 0.5 m and altimetric resolution of 0.3 m corresponding to the IGN's NUALID LiDAR (less than 10 pulses per m²). In June 2021, IGN collected new LiDAR HD images (point density > 10 pulses per m²) for the Alpes-Maritimes as part of the national LiDAR coverage program (IGN 2021). In ArcGIS Pro 3.1.2 (ESRI Inc.), two sets of point clouds have been classified to generate a digital terrain model, DTM_{2021} and a digital surface model, DSM_{2021}. The DTM_{2021} and DSM_{2021} have a planimetric resolution of 0.5 m and an altimetric resolution of 0.1 m (IGN, 2023a). A digital terrain model (DTM) provides information about the elevation of terrain features, typically represented as a grid of elevation values. A digital surface model (DSM) includes the elevations of natural and artificial features, such as trees, buildings, and other structures. It provides a detailed and accurate depiction of the terrain's topography, including surface features.

The Roya Valley's latest (pre-flood) digital terrain model (RGE Alti ®) dates from 2008 and is of poor quality for mountainous areas. In fact, radar acquisitions have been favored in mountainous and steeply sloping areas, reducing altimetric accuracy to an average of 7 m (IGN 2018). Only valley floors were imaged with acceptable resolutions, although they are not helpful for in steeply sloping areas. Before October 2020, no LiDAR images cover the entire Roya Valley.

The only good quality data prior to the event is the correlated digital surface model ("MNS Correl" produced by IGN), which has an altimetric error of + / − 0.2 m (IGN 2023). The Correl DSM is a

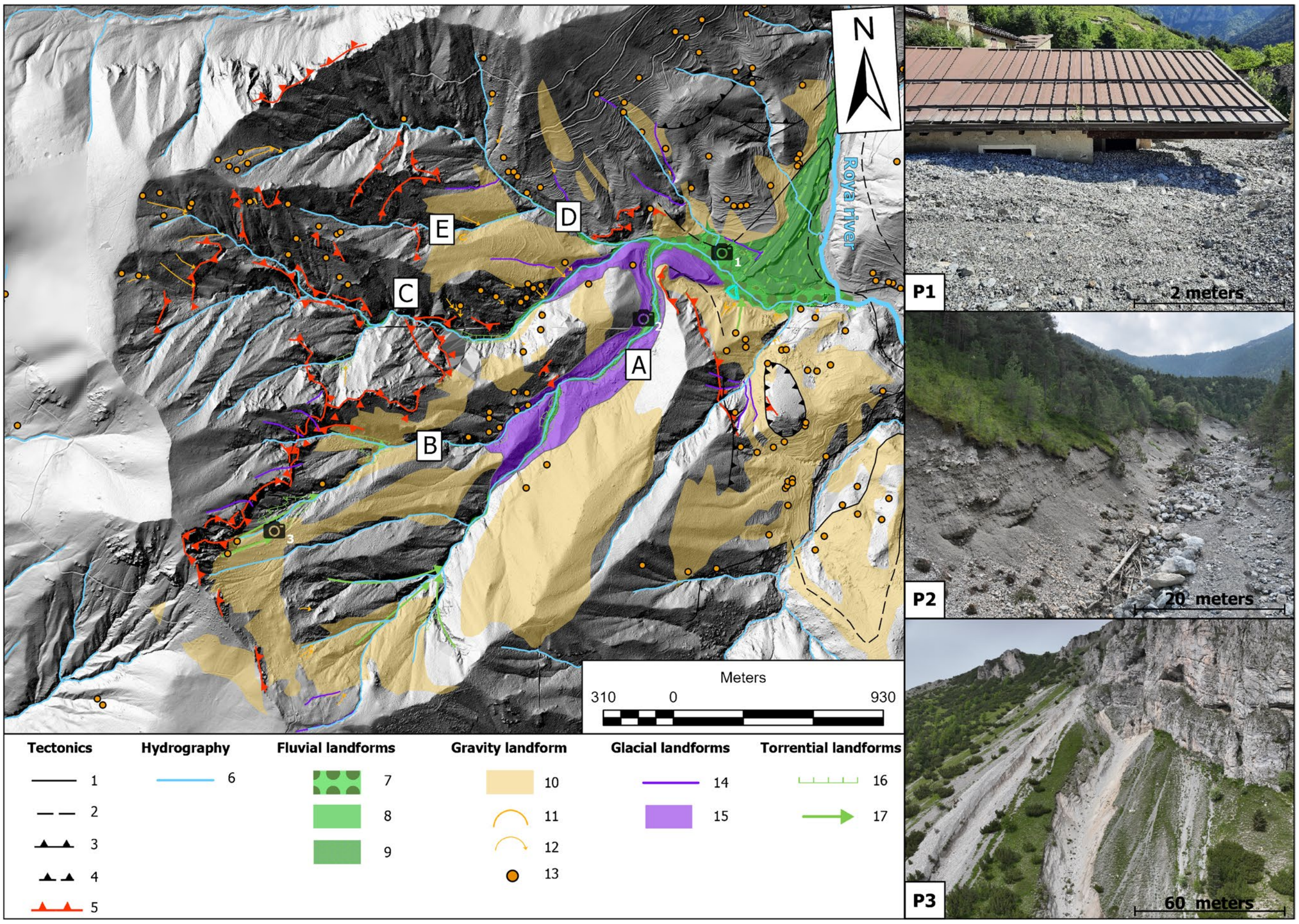

Fig. 3 (A) Left. Geomorphological map of the Vievola catchment area. Data was combined with the 1:50,000 BRGM map (Gèze and Nesteroff 1996) and reports from the ONF, RTM, and INRAE. **A** Vallon de Dente, **B** Vallon de Rabay, **C** Vallon de Morte, **D** Vallon de Para, and **E** Vallon de Scabrie. 1, fault; 2, supposed fault; 3, thrust; 4, supposed Thrust; 5, rocky escarpment; 6, rivers/torrents; 7, alluvial fan (Alex 2020); 8, fluvial accumulation; 9, alluvial fan (Pléistocene); 10, scree; 11, scarps; 12, scree corridor; 13, landslides; 14, glacial striae; 15, fluvio-glacial outwash; 16, torrential scarp; 17, major gully. (B) Photo 1—Alex flood debris flows engravelling one of the buildings of the Viévola camp resort during the Alex storm flood (5 July 2021). Photo 2—Dente torrent after the flood, on the left side, we can see the glacial fluvial outwash deposits. Photo 3—Major gullies observed at the headwaters of the Rabay area

regular grid of altitudes representing the ground or surface without differentiation obtained through the correlation of aerial images. The correlation is a process that automatically detects corresponding points between different captures of the same scene. The intersection of these corresponding beams, thus reconstructed, allows deducing the XYZ coordinates of the point in the scene (IGN 2023). This raster, named herein DSM_{2020}, constitutes our reference before the flood and will be compared with the LiDAR dataset acquired after event DTM_{2021}.

The cumulative altimeter error for DSM_{2020} and DTM_{2021} is within the range of +/−0.3 m.

In addition, several drone surveys were carried out in March, June, and October 2023 (Fig. 3B, Photo 2) in the Viévola catchment area, with a DJI Mavic 3^{E} including a RTK module and an Orpheon subscription (enabling correct geo-referencing for the orthoimages). Photogrammetric models were processed with Agisoft Metashape 1.8.3 Pro software and exported to ArcGIS Pro 3.1.2 (ESRI Inc.) to map the eroded and transported sediments and volume quantification.

Methodology

To ascertain the sediment volumes eroded and deposited within the Viévola catchment area, we employed the DSM_{2020} as our pre-Alex data and the DTM_{2021} for the post-Alex assessment. Despite the DTM_{2021} dataset being acquired 8 months subsequent to the post-Alex LIDAR 2020, it was deemed more suitable owing to its higher resolution. The post-Alex 2020 data (raw LiDAR NUALID) necessitated calibration, noise reduction, and correction for ellipsoidal height, a process not requisite for the DTM_{2021}. Notably, no significant changes happened during the time lapse after the Alex flood and July 2021 since the period was characterized by very low precipitations (see supplementary data). Herein, the sediment volumes that are eroded and transported are considered **ground erosion.**

For volume determination, we initially performed a topographical comparison (Eq. 1):

$$DTM_{2021} - DSM_{2020} = \Delta DSM \tag{1}$$

The ΔDSM denotes the altimetric difference between the two datasets. In areas impacted by the storm, the ΔDSM provides insights into the total erosion during the flood (Fig. 4), encompassing both the canopy height and the eroded ground thickness. In vegetation-free areas, the *ΔDSM* exclusively represents the soil ground (Fig. 4). For areas unaffected by the storm, the canopy height is indicated. Total erosion in vegetated areas is formulated as (Eq. 2):

$$\Delta\text{DSM} = \text{"}\textit{Tree cover thickness}\text{"} + \textbf{\textit{Ground erosion}} \tag{2}$$

Equation 1 can extract ground erosion from the ΔDSM by employing the average canopy height (i.e., tree cover) in flood-affected areas. As a result, ground erosion in flood-impacted zones is isolated. From Eq. 2, we can define the **ground erosion** as:

$$\textbf{\textit{Ground erosion}} = \Delta\text{DSM} - \text{"}\textit{Tree cover thickness}\text{"} \tag{3}$$

Herein, “tree cover thickness” pertains to the height of trees uprooted during Storm Alex, determined by deducting an average tree height from the DSM_{2020}.

This brings us to determine two zones of interest:

i) Low vegetation zone (0–0.5 m, according to IGN 2023) where the surface of the DSM corresponds to the surface of the DTM. This can be expressed as follows from Eq. 1: ***Grounderosion*** = ΔDSM with tree cover thickness = 0

ii) Vegetated zone (> 0.5 m) where we know the total erosion, i.e., ΔDSM (Eq. 1)

Before determining the mobilized volumes, we verified that the altimetric information in the DSM_{2020} is the same as that in the DSM_{2021}. First, we calibrate the DSM_{2020} with respect to the DSM_{2021} (the DSM_{2021} is taken as the reference because it has the best resolution and the smallest altimetric error margin) in low vegetated zones and vegetated zones unaffected by Storm Alex. We obtain – 0.21 m for low vegetated zones and – 1.97 m for all vegetated slopes in the watershed. To be more precise, this calibration difference has been estimated at the scale of each sub-valley of the studied torrent (see supplementary data). The

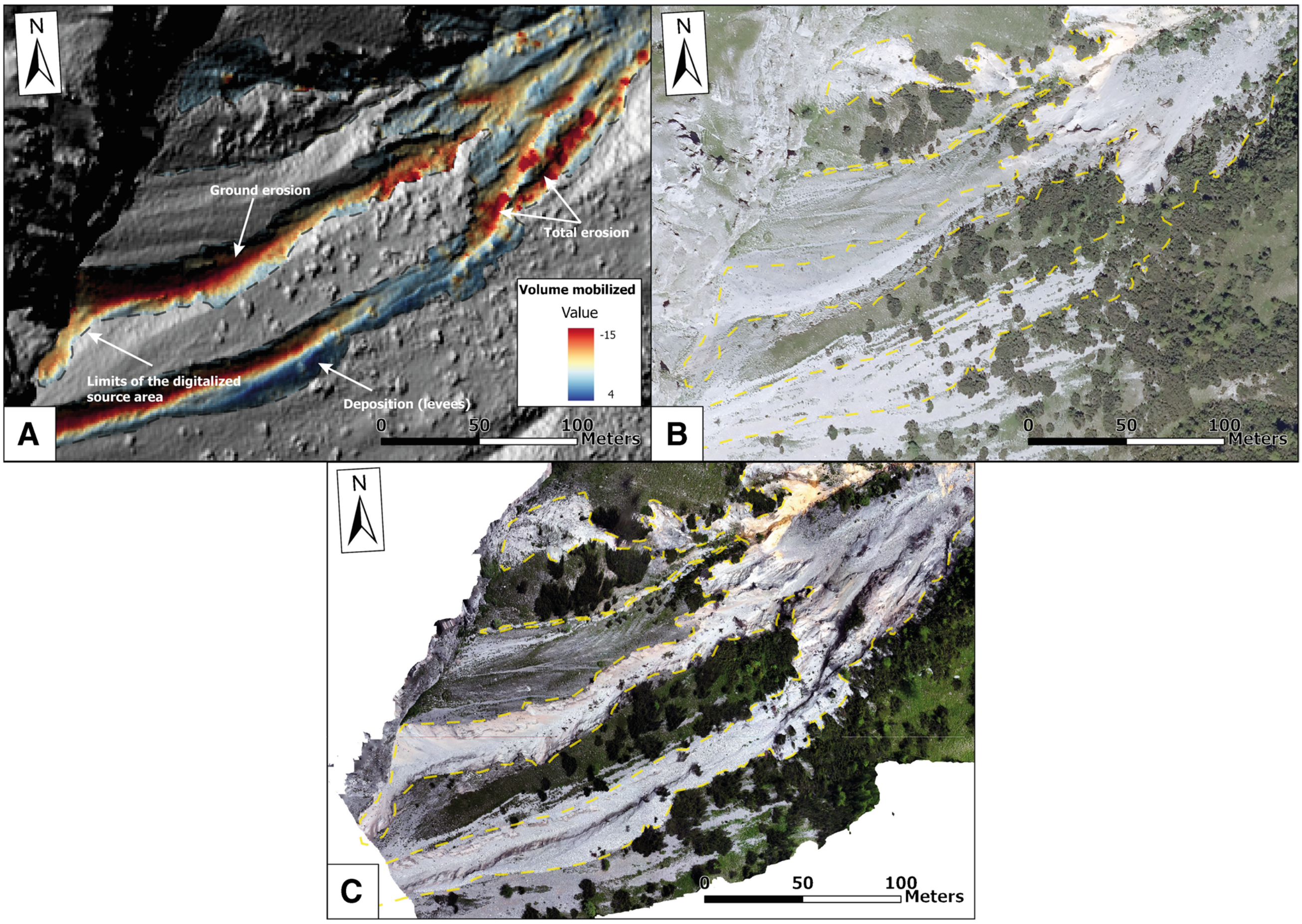

Fig. 4 Illustration of altimetric differences at the head of the Rabay valley gullies (DTM_{2021}–DSM_{2020}) across different temporal scales: **A** DSM_{2021} post-flood, **B** orthoimages from July 2020 (pre-flood), and **C** orthoimages from October 5 to 7, 2020 post-flood. **A** Overlaid with the outcome of Eq. (1), delineating erosion zones (in red) and deposition zones (in blue). The delineated working area is marked by the dashed yellow line. In these visuals, we can observe areas with sparse vegetation where DSM_{2020} equals DTM_{2021}, allowing for direct estimation of **ground erosion**. Total erosion is notably pronounced in certain areas, reaching maximum values of up to – 15 m

negative value indicates an elevation of the DSM_{2020} compared to the DSM_{2021}.

In order to distinguish tall vegetation, primarily trees in the vegetated area, we selected areas unaffected by Storm Alex from false-color composite images (BD Ortho IRC) produced by IGN for the Alpes-Maritimes in 2017. The IGN's IRC operates on three bands: the first corresponding to the NIR, the second to the red band, and the third to the green band. NDVI (Normalized Difference of Vegetation Index) indices were calculated using the two first bands of false-color composite images. The fundamental principle of NDVI is that healthy vegetation absorbs most of visible light for photosynthesis (Tucker, 1979; Sellers, 1987) while reflecting a significant portion of near-infrared light. Sparse and unhealthy vegetation, on the other hand, reflects more visible light and less near-infrared light. By measuring the difference in reflectance between red and near-infrared bands, NDVI provides information about vegetation health and density. The NDVI is calculated using the following formula Eq. 3: $DVI = \frac{(NIR-Red)}{(NIR+Red)}$.

where NIR represents reflectance in the near-infrared band, and red represents reflectance in the red band. Values range from -1 to 1, with negative values corresponding to water. Values near 0.1 indicate bare soil, snow, or sand, an index between 0.2 and 0.3 corresponds to grasslands and bushes, and between 0.6 and 0.8 corresponds to tropical forests (Holben 1986).

Table 2 The average tree heights were obtained after recalibrating the data using the methodology outlined above. Only the valleys of Dente, Rabay, and Morte were considered, as they have clearly identifiable source zones (landslides, ravines), unlike the Para and Scabrie torrents

	Dente	Rabay	Morte
Average height trees	10.6 +/− 0.3 m	9.2 +/− 0.3 m	9.5 +/− 0.3 m

In order to identify trees and the distribution of tree heights, we established an arbitrary vegetation detection threshold based on Derrien et al. (1992) of > 0.30 (see supplementary data). For each studied torrent (Fig. 2), we extract the height of trees on their slopes using the method outlined above and estimate an average height after recalibration on the basis of the difference in elevation between DSM_{2021} and DSM_{2020} given in Table 2. The height of these trees is employed for subtraction from the DSM_{2020} (Table 3).

For the volumes deduced from Eq. 1, an error margin of ± 0.3 m is applied.

This methodology is applied in two major erosion zones: (i) source areas such as gullies and landslides and (ii) bank erosion. It is also applied to the Viévola alluvial fan to determine deposited volumes. This approach allows us to estimate a sediment volume balance between the source (erosion) and deposition zones.

Results and discussions

The volumes eroded within the five torrents in the Viévola catchment are presented in Table 3. Erosion related to the event in these torrents is divided into three categories (gullies, bank erosion, and landslides), as explained above with their associated error margins. The transport of the mobilized volumes (Table 3) results in a total volume deposited in the Viévola alluvial fan of 88,500 m^3 +/− 19,670 m^3 (Fig. 5).

The main contribution in sediment came from the Dente and Rabay Valleys (Table 3), totalling approximately 144 300 m^3 (80% of the total erosion) with a margin of error of approximately 15 000 m^3. Notably, the heads of the gullies in the Dente and Rabay Valleys, situated in unconsolidated scree slopes, produced between 36 900 m3 and 46 000 m3, respectively (Table 3, Fig. 4).

The Dente valley is characterized by significant bank erosion, contributing 57,200 m^3 of sediment (31% of the total erosion). Landslides made a negligible contribution of 802 m^3 (Table 3) and 656 m^3 in the Dente and Rabay, respectively. The ratios yield the following results: 1.4 m for ravines, 2.1 m for bank erosion, and 2.6 m for landslides. Landslides have the highest ratio compared to

Table 3 Volumes eroded within the five torrents in Viévola catchment during the Alex storm. Each erosion value holds the uncertainties defined using the previous methodology. A total of 179,431 m^3 of sediments were released during the flood. The total surfaces studied for the gullies volumes is 67,210 m^2, for bank erosion is 27,444 m^2, and landslide is 8733 m^2. The last line corresponds to the ratio between the eroded volumes and the surface area

Names	Gullies volumes		Bank erosion		Landslides		Total	
	Erosion (m^3)	Margin error (m^3)	Erosion (m^3)	Margin error (m^3)	Erosion (m^3)	Margin error (m^3)	Erosion (m^3)	Margin error (m^3)
Dente torrent	36,900	4059	57,200	3040	802	240	94,900	7340
Rabay torrent	46,000	7366	2720	250	656	197	49,420	7813
Morte torrent	14,000	3100	–	–	16,700	5004	30,644	8107
Para torrent	–	–	–	–	3800	1140	3800	1140
Scabrie torrent	–	–	–	–	667	200	667	200
Total	96,900	14,525	59,920	3290	22,625	6781	179,431	24,600
Surfaces (m^2)	67,210		27,444		8733		103,387	
$\frac{m^3}{m^2}$	1.4 m		2.1 m		2.6 m		1.7 m	

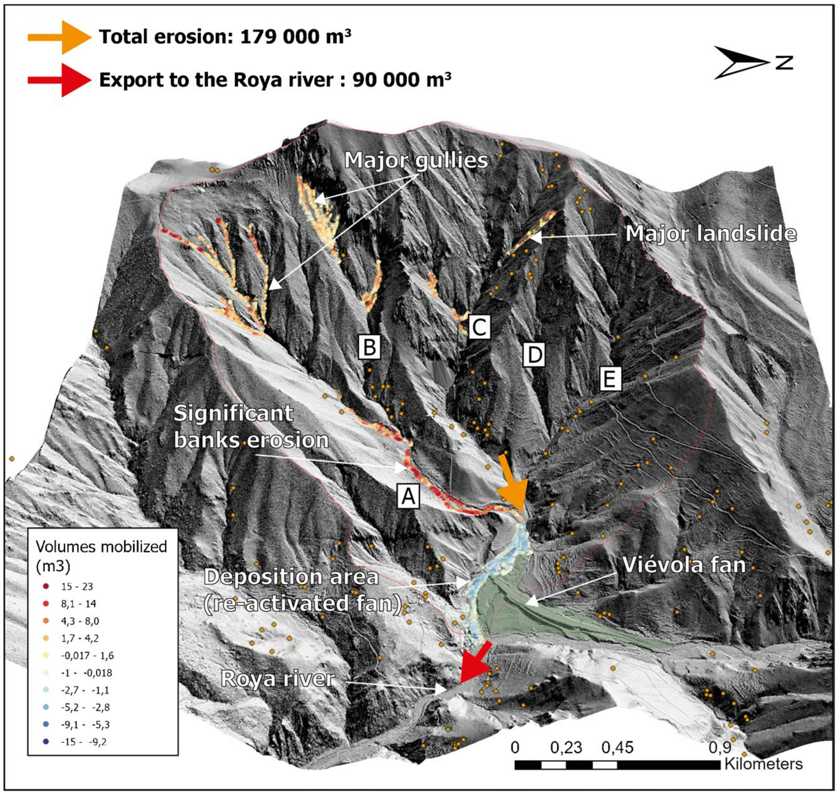

Fig. 5 Spatial representation of mobilized volumes in the Viévola watershed, including calculated erosion and deposition areas based on the methodology outlined above. The geomorphological map (Fig. 2) provides a plan view of the study area. **A** The Dente torrent, **B** the Rabay torrent, **C** the Morte torrent, **D** the Para torrent, and **E** the Scabrie torrent. Thin red line represents Viévola catchment. The orange dots represent landslides that occurred during the event. The green polygon represents the surface area of the Viévola fan, estimated to be 250,000 m^2 using ArcGIS Pro. Erosion areas are indicated by yellow to red dots, with their surfaces detailed in Table 3. Blue dots correspond to deposition on the Viévola fan, with an estimated surface area of 67,036 m.^{2}

ravines. Notably, the sediment contribution from the banks was particularly significant, with a ratio exceeding 2 m. The contrast in bank erosion between these valleys can be attributed to two main factors.

Firstly, the Rabay River features a by-pass zone with a slope of around 30° where deposition is not feasible, and Jurassic/Cretaceous limestone is outcropping. Bank erosion is prominent at the exit downstream of the bypass zone, several hundred meters upstream of the confluence with the Dente torrent, where the gradient becomes milder (Figs. 2 and 4). The second factor is the presence of glacial outwash deposits (Fig. 2) associated with the last glaciation and/or the Little Ice Age (Julian 1997; Brisset et al. 2015; ONF-RTM, ONF-DRN and INRAE-ETNA 2023). As depicted in Fig. 2, the downstream section of the Dente torrent is composed of this unconsolidated lithology. The observed deposits on the Viévola alluvial fan correspond to cryoclastic deposits (Fig. 3(P1)), reinforcing the notion of substantial erosion of fluvio-glacial outwash deposits.

Sedimentary analysis of the deposits in the Dente torrent reveals a succession of debris flows characterized by typical sedimentary fronts and deposits. The force of such a flow is assumed to allow increased erosion of unconsolidated deposits (Fig. 3(P2)), which, in this case, are the source of this substantial input from the banks of the Dente Valley (Fig. 5).

The Morte, Para, and Scabrie torrents have produced less sediment (Table 3 and Fig. 5). This may be explained by the fact that these valley heads lack large gullies, unlike the Dente and Rabay Valleys (Fig. 2 and P3 in Fig. 3). Notably, the heads of these sub-catchments do not feature scree slopes (Fig. 2). However, there is a higher density of landslides. A significant landslide of approximately 13,000 m^3 occurred at the head of the Morte torrent (Fig. 5), accounting for 54% of the sediment release upstream of this tributary. There is an apparent disparity in the contributions that landslide processes provide.

Orthoimages produced by IGN before and after the event reveal that most of the contributions from the Scabrie, Para, and Morte torrents are linked to the widening of the channel, indicating significant lateral erosion, though less pronounced than the Dente torrent.

At present, erosion and deposition within the torrent channels have yet to be estimated. Hence, the values indicated in Table 3 reflect a low range of eroded volumes. The topographic difference observed represents only the end state. During the event, one or more erosion phases may have occurred, significantly incising the heart of the torrents and generating a substantial sediment input. In some cases, certain zones correspond solely to channel aggradation without erosion. These nuances cannot be accurately quantified with our datasets, and sediment balances may be "distorted" as a result. Into the inner channel, significant erosion may occur, and a few hundred meters further downstream, erosion deposits may be found. Consequently, a zero balance may be observed when calculated on a GIS. To simplify our analysis, we have chosen to focus on erosion at the head of the catchment area (gullies, landslides) and the outlet (alluvial fan), as well as bank erosion when particularly pronounced. This approach explains the limited additional information for the Morte, Para, and Scabrie valleys, as these torrents likely generated more sediment.

The volume deposited at the Viévola fan computed is 88,500 m^3 (Fig. 5). This result aligns with the information provided by the ONF and the RTM following Storm Alex, which estimates the volume of the Viévola fan at 90,000 m^3 (ONF-RTM, ONF-DRN and INRAE-ETNA 2023).

The deposition area on the Viévola fan covers 67,036 m^2 (Fig. 5). When calculating the ratio of deposited volume to surface area ($V_{\text{deposited}}$ / surface), we obtain that, on average, the area was engraved by 1.3 m across the entire surface of the reactivated fan during the event, with very significant maxima reaching up to 9 m in height, as illustrated in the ONF-RTM, ONF-DRN, and INARE-ETNA report from 2023.

Across a total area of approximately 250,000 m^2 on the fan (Fig. 2 and Fig. 5), there are railway facilities, bridges, residences, and a holiday camp. Roughly 26% of the fan area was reactivated by the mentioned torrents, resulting in the engraving of buildings in the holiday camp (Fig. 2). The SNCF (French National Railway Company) bridge was also affected, contributing to the interruption of railway traffic to that area. Furthermore, the expansion of the active band of the Roya River on the eastern part of the alluvial fan also played a role in depositing/eroding a portion of it, leading to the destruction of bridges and roads. These advantageous reliefs, with their gentle slopes in a particularly narrow valley, offer opportunities for land use. Traditional floods only minimally affect or do not impact alluvial fans, leaving them inactive. However, during extreme events like Alex's, a significant portion of fan surface was reactivated, causing destruction and cutting off access to the population.

Considering both produced and deposited sediments, the analysis reveals that more 90,000 m^3 were discharged into the Roya River. In relative terms, the sediment deposited was relatively small, contrasting with the substantial export into the Roya. These sediments have played a crucial role in significant erosions and morphological changes, impacting anthropogenic infrastructure along the entire stretch of the Roya River (approximately 60 km). This situation resulted several weeks of isolation for the affected valleys, necessitating states of emergency declarations.

Conclusions and perspectives

In conclusion, our study has highlighted the significance of the Viévola catchment area as a significant sediment source of sediment, with particular importance of the Dente and Rabay torrent heads. Erosion during the extreme storm event was most pronounced in areas characterized by scree and outwash fluvio-glacial deposits. Despite the lack of a high-quality digital terrain model (DTM) before the event, our straightforward method, based on a digital surface model (DSM) derived from autocorrelation of high-quality orthoimages, enabled us to estimate sediment volumes, both exported to the Roya River or deposited inside the Vievola catchment area. These results provide valuable insights into the geomorphological response of slopes and rivers to extreme events. Extending our study to the entire Roya Valley holds the promise of deepening our understanding of factors that predispose mountainous areas to such events, triggers of extreme hydro-sedimentological events, and morphological changes that occur within catchment areas following significant incidents. Combining digital data with information collected during field campaigns conducted in March, June, and October 2023 can further enhance our understanding of the extreme water–sediment flow processes. This comprehensive approach will make it possible to characterize and model this type of extreme event, and thus to be better prepared to manage similar extreme events in the future.

Acknowledgements

We express our sincere gratitude to all those who have contributed to this research. The authors acknowledge the support of the ANR-17-CE03-004-01 project, the "coup de pouce" project of ISTeP Sorbonne University, and the doctoral fellowship from the French Research Ministry for funding this study. Additionally, we would like to extend our thanks to the Institute of Ocean and Environmental Transition of the Alliance Sorbonne University for financing three field campaigns. We are grateful to the Monastery of Saorge (Center for National Monuments) for providing accommodation for researchers. We also recognize the MITI of CNRS for funding the equipment used in this study. Finally, our appreciation goes to Nicoletta BIANCHI from the Musée des Merveilles in Tende (Alpes-Maritimes department) for her invaluable assistance in the field. I express my gratitude to the two reviewers whose constructive comments have significantly enhanced the quality of this work.

Data availability

Data can be requested from the author.

Declarations

Conflict of interest The authors declare no competing interests.

References

Blanchard R (1949) 'Tome cinquième : les Grandes Alpes françaises du Sud', in *Les Alpes occidentales*. Grenoble et Paris: Arthaud, p. 514

Brisset E et al (2015) Lateglacial/Holocene environmental changes in the Mediterranean Alps inferred from lacustrine sediments. Quaternary Sci Rev 110:49–71. https://doi.org/10.1016/j.quascirev.2014.12.004

Carrega P, Michelot N (2021) Une catastrophe hors norme d'origine météorologique le 2 octobre 2020 dans les montagnes des Alpes-Maritimes. Physio-Géo 16:1–70. https://doi.org/10.4000/physio-geo.12370

Cerema (2021) RETEX technique ALEX - Inondations des 2 et 3 octobre 2023. consensus hydrologique - Unpublished report - CEREMA, p. 59

Derrien, M. *et al.* (1992) 'Classification de la végétation sur la France à l'aide de l'AVHRR de NOAA-11', *Norois*, t. 39(155), pp. 269–282

Gèze B, Nesteroff N (1996) *Carte géologique de la France à 1/50 000. Feuille : 973 - Menton - Nice*. Orléans: Editions du BRGM

Holben BN (1986) Characteristics of maximum-value composite images from temporal AVHRR data. Int J Remote Sens 7(11):1417–1434. https://doi.org/10.1080/01431168608948945

IGN (2018) RGE ALTI® Version 2.0 - Descriptif de contenu, p. 37

IGN (2020) *Un avion de l'IGN photographie les zones sinistrées*, *un avion de l'IGN photographie les zones sinistrées*. Available at: https://www.ign.fr/institut/nos-domaines-dintervention/prevention-des-risques/tempete-alex-un-avion-de-lign-photographie-les-zones-sinistrees

IGN (2021) *Lidar HD : vers une nouvelle cartographie 3D du territoire*, *Lidar HD : vers une nouvelle cartographie 3D du territoire*. Available at: https://www.ign.fr/institut/lidar-hd-vers-une-nouvelle-cartographie-3d-du-territoire

IGN (2023) *MNS Correl Version 1.0 - Descriptif de contenu*. French National Institute of Geography, p. 12

Julian M (1980) *Les Alpes maritimes franco-italiennes: étude géomorphologique*. Université de Lille III

Julian M (1997) 'Les glaciations des Alpes Maritimes : essai de mise au point.', in *Géo-Méditer : Géographique physique et méditerranée*. Editions de la Sorbonne, pp. p245–261

Liébault F et al (2024) Channel change during catastrophic flood: example of Storm Alex in the Vésubie and Roya valleys. Geomorphology 446:109008. https://doi.org/10.1016/j.geomorph.2023.109008

ONF-RTM, ONF-DRN, and INRAE-ETNA (2023) 'Retour d'expérience technique de la crue du 2 octobre 2020 dans la vallée de la Roya - Volet torrentiel'. Recherche Data Gouv https://doi.org/10.57745/B69M2O

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10346-024-02361-2.

Raphaël Kerverdo (✉) · **Sara Lafuerza** · **Christian Gorini** · **Alain Rabaute**
Institut Des Sciences de La Terre de Paris (ISTeP), Sorbonne Université, CNRS-INSU, 75005 Paris, France

Raphaël Kerverdo
Email: raphael.kerverdo@sorbonne-universite.fr

Didier Granjeon · **Rémy Deschamps**
IFP Energies Nouvelles, Rueil-Malmaison, France

Eric Fouache
Laboratoire Médiations, Institut de Géographie, Sorbonne Université, Paris, France

Mina Jafari · **Pierre-Yves Lagrée**
Institut Jean Le Rond d'Alembert, Sorbonne Université, Paris, France