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High velocity geomorphological processes in a tropical area: the Remparts River case study (Réunion Island, Indian Ocean)

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Abstract

The Reunion Island is characterized by rapid landscape evolution resulting from its cyclonic tropical climate. However local active surface processes are not well understood. The relationships between climatic events, large scale landslides and torrential transport of sediment by the rivers remain unclear. The Remparts River is an appropriate area for studying such geomorphological processes, as it deeply incises the active *Piton de la Fournaise* volcano. In this study, different approaches are used to analyze the morphological evolution of the river from the sediment production areas to the outlet over the last 40 years. Recurrent events of huge mass wasting occur at Mahavel Cliff, upstream of one of the river tributaries, the most recent producing around $50 \times 10^6 \text{ m}^3$ of sediment in 1965. Combined analyses of the sequence of cyclonic events, major mass wasting events and aerial photography interpretation over the last 40 years lead to the proposition of a functional model of river system responses to these events. The river system can be divided into three compartments, each affected by three classes of geomorphological events. The sedimentary response (erosion and/or aggradation) of each compartment to a triggering event, such as cyclonic rainfall and/or seasonal rise of water discharge, is controlled both by the magnitude of the climatic event and by the state of the compartment resulting from previous evolution. A set of 5 aerial photographs and a satellite image showing the evolution of the studied area during the last 40 years are examined in detail in the light of the functional model. Observations confirm a rapid and complex evolution of the river bed (erosion and aggradation), and provide information about the dynamics of the sediment transfer from the production areas to the ocean. Analysis of two distinct topographic datasets bracketing the last major cyclone (Dina 2002), allows the estimation of the river sediment budget resulting from this event. The net volume of aggraded sediments in the river bed is estimated at around $8 \times 10^6 \text{ m}^3$.

With no major collapse event recorded at Mahavel cliff, sediment transfer due to the flood associated with the 3 days cyclone Dina event is responsible for this significant increase in river bed sediment volume. This quantification shows that several million cubic meters of sediment may take only a few years to spread over more than 5 km downstream. The river bed has now reached its highest elevation since the 1965 landslide, with potential consequences for natural hazards in the area of the outlet at the city of Saint-Joseph.

Keywords

Reunion Island, fluvial geomorphology, cyclones, torrential processes, debris flow, quantification

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1. Introduction

Quantification of geomorphological changes and rates of landscape evolution is a matter of primary importance, as much in natural hazards studies (e.g., Pasuto and Soldati, 2004) as in calibration of landscape evolution models (e.g., Hancock et al., 2002, Bogaart et al., 2003, Garcia-Castellanos et al., 2003). It is important to study places where morphological changes are rapid enough to allow measurements to be made that reflect actual surface processes, while avoiding a large observation window which may smooth or even erase the short-term evolution. Certain tropical islands suffer extreme climatic conditions that can give rise to particularly rapid landscape evolution. Some volcanic islands especially are known to experience very active erosion, because they generally exhibit a pronounced relief, thus enhancing surficial processes (Thouret, 1999, Oguchi et al., 2001). In such places, heavy and frequent rainfall can trigger landslides, debris flows and intense erosion. Numerous studies of climatic-induced intense morphological processes were thus conducted in suitable regions like New Zealand (Page et al., 1994, 1999, Reid and Page, 2002), Indonesia (Lavigne and Thouret, 2002), or the Fiji islands (Terry et al., 2002).

In this paper we investigate morphological processes in a catchment of Reunion Island, which exhibits both a cyclonic tropical climate and a pronounced relief (3000 m for an average diameter of 50 km). In such a context, rivers are affected by torrential flows in which the mean flow velocity in the open channel is greater than the propagation velocity of the waves. In this paper, the term « torrential » includes all the processes associated with such a regime (debris flow, hyperconcentrated flows, high energy bedload transport).

Current research on the surface processes influencing Reunion Island morphology is limited. Some recent studies have focused on large scale processes, such as debris avalanche degrading the volcano construction (Bret et al. 2003, Fèvre et al. 2003). Several land planning studies focused on the hydraulic and hydrological aspects of the present torrential dynamics (SOGREAH, 1992, BCEOM, 2000). The evolution of local hydrosystems and morphogenetic process dynamics have been examined principally in public utility studies (Humbert 1986, Garcin et al., 1997, Garcin and Cruchet, 2001, Pouget and Garcin, 2003), and through geochemical measurements of long-term erosion rates (Louvât and Allegre, 1996, 1997). Geomorphological studies pointed out the magnitude of the morphological processes in this region, and suggested the possibility of very high rates of landscape evolution. Nevertheless, the only quantitative study has been conducted to confirm this idea is the geochemical work which could not explain the very incised landscape of the island (Louvât and Allègre, 1996).

We focus on the Remparts River valley, which is flanked by up to 1000 m high cliffs, while its width does not exceed 1 km. During the last few decades, the river was massively fed with sediments, essentially provided by cliff collapses occurring in one of its tributaries, in particular in 1965 when the volume of the collapse was estimated at $50 \times 10^6 \text{ m}^3$ (BRGM, 1965). In this paper, we analyze sequences of mass wasting events, cyclonic events, and main morphological changes, with the intention of understanding how morphological processes respond to both sedimentary and climatic signals. We propose a functional analysis of the behaviour of the river system in response to mass wasting and climatic events. Furthermore, we use topographical data from different sources to provide an estimation of the sediment budget related to a recent cyclone event.

2. Geographic and geomorphic settings

Reunion Island is located in the western Indian Ocean (55°30'E, 21°S; Figure 1). The local tropical climate is characterized by two seasons: a dry season during the austral winter, and a wet season (when cyclones may occur) during the austral summer. Precipitation is highly variable in time and space. Reunion Island is made up of two basaltic volcanoes, resulting from hotspot activity. The "Piton des Neiges" the oldest of the two with a radiometric age determined at 3 My was active until 12 ka BP (Rocher, 1988). The "Piton de la Fournaise" is located in the southern part of the island (Figure 1). It emerged around 530 ka BP and is still

active today (Gillot and Nativel, 1989). Relief of the island is very strong, enhancing erosive processes that affect the volcanic building.

The Remparts River is the main river of the Piton de la Fournaise massif (Figure 1). It flows from North to South for 24 km, draining a watershed of about 65 km^2 . Three tributaries are located on the eastern side, (Figure 2): the Caron reach (6.9 km^2), the Mahavel reach (8.5 km^2), and the Dimitile reach (4.8 km^2). Average annual precipitation over the watershed ranges from 3000 to 4250 mm/yr.

The catchment asymmetry is controlled by the east-dipping Piton de la Fournaise volcanic units (up to 30° , see Mairine and Bachelery, 1997). In the upstream zone valley width ranges from 100 to 400 m and the river is deeply embanked between steep cliffs ("Remparts"), which reach 1000 m high in places. The downstream zone corresponds to the last 3.4 km before the outlet. It consists of a 35 m wide bedrock channel bordered by 10 m high basaltic banks. Three topographic steps, 6 to 8 m high are present in the area of the city of Saint-Joseph.

The upstream part of the Mahavel reach consists of the so called "Mahavel Cliff" (Figure 2). This 1000 m high cliff has experienced several collapses during the last century. One of these collapses, probably the most significant event, occurred on 6 May 1965. On this occasion, the volume of collapsed material was estimated at between 30 and $50 \times 10^6 \text{ m}^3$ (BRGM, 1965). During this event, products stemming from the collapse buried the whole Mahavel reach, and were carried to the confluence with the Remparts River. This sediment supply created a natural dam across the Remparts River, forming a lake with a capacity of $14 \times 10^6 \text{ m}^3$ of water (BRGM, 1966).

The risk of this dam breaking and releasing a huge quantity of debris toward the city of Saint-Joseph located at the river outlet was a source of anxiety for the local authorities. (Figure 2). Apart from the Mahavel reach, the two other tributaries and the upstream part of the Remparts River currently do not supply a significant amount of sediment. The totality of the solid load is thus produced by the Mahavel reach.

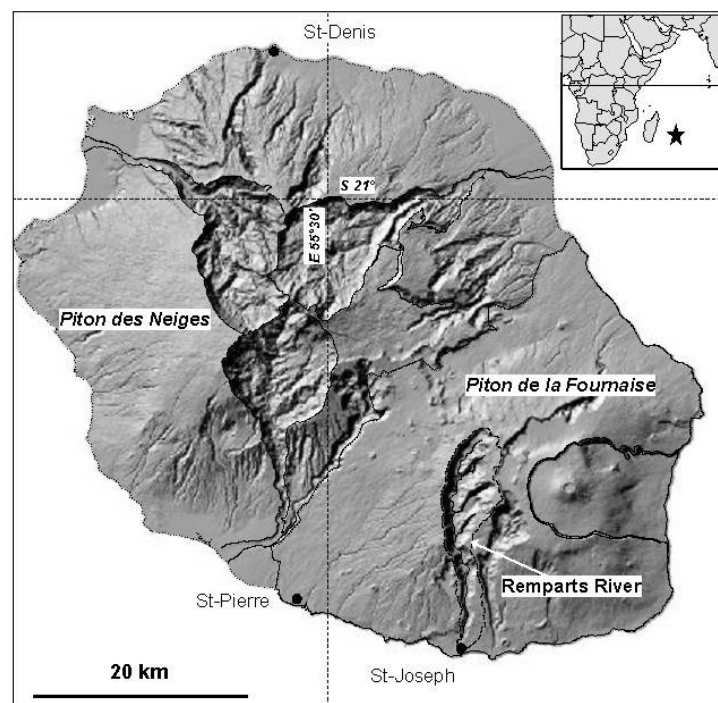


Figure 1. Location map of Reunion Island.

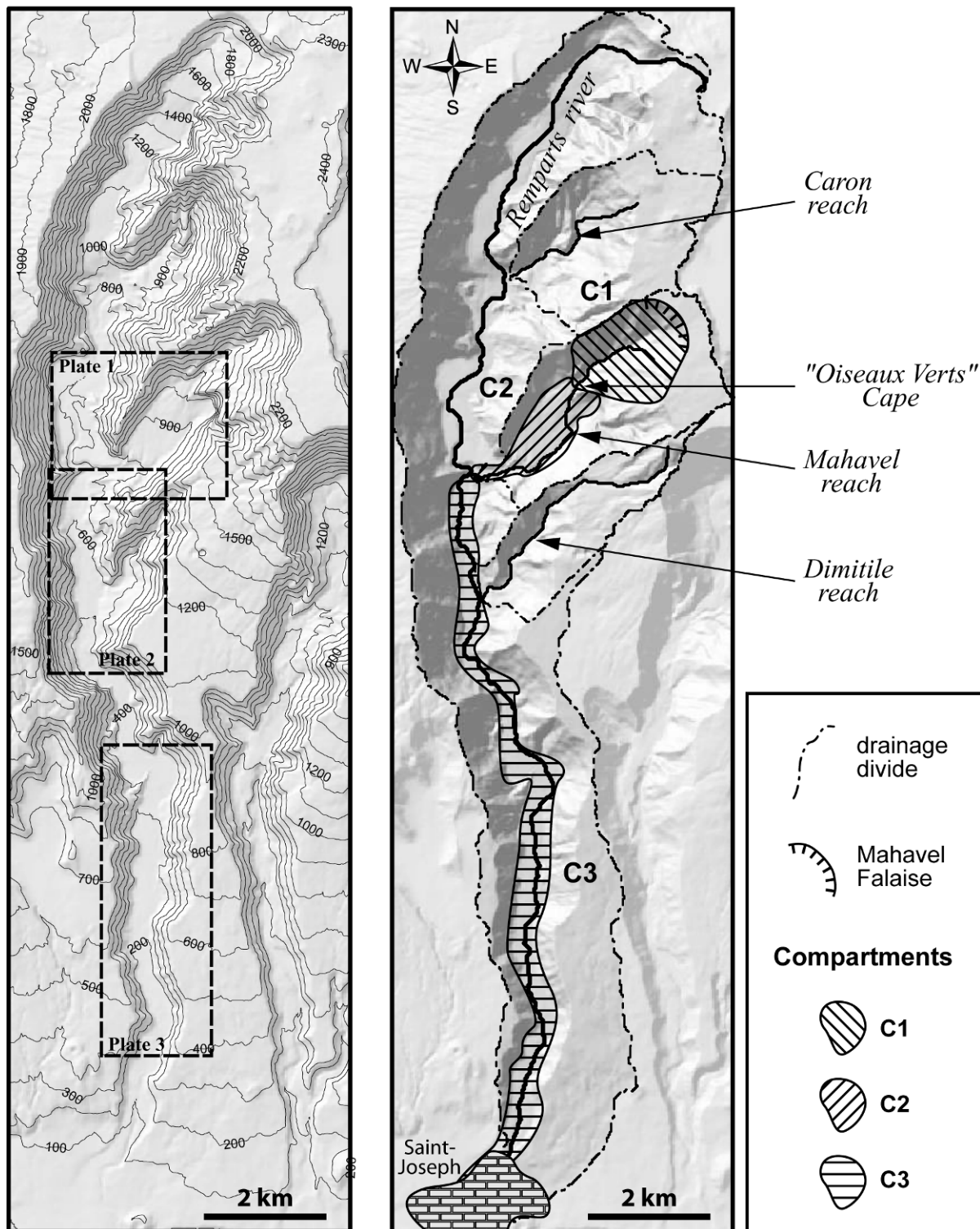


Figure 2. The Remparts river - (left) Topographic map of the Remparts River watershed (shaded relief and contour lines, 100 m intervals, from the 25-m DEM provided by the IGN). Dashed boxes show location of areas detailed in Plates 1, 2, 3. (right) Situation map of the same zone showing the tributaries and respective boundaries of the three compartments brought out from the functional analysis of the Remparts river (see explanations in the text).

3. Systemic approach of the Remparts River

The objective of the systemic approach here is to give a thorough description of the main components and functions of the Remparts River watershed. Observations of geomorphological changes and associated processes will then be interpreted according to the described system.

3.1. Forcing factors for river morphology

External constraints on morphological evolution are well known. They essentially consist of major climatic events such as cyclonic storms which are responsible for huge quantities of rainfall on the Remparts River watershed. According to their intensity, these heavy rains may trigger either bedload transport in the river network, or debris flows. Mass wasting around Mahavel Cliff and landslides on hillslopes are mainly triggered by climatic events, but they may also be influenced by earthquakes, induced by the volcanic activity of the Piton de la Fournaise. The temporal pattern of these external constraints are presented below.

PROFILES

Longitudinal topographic profiles of the Remparts River, Dimitile reach and Mahavel reach are presented in Figure 3. This figure shows the steep profile of the river channel (4% gradient for the Remparts River downstream of the confluence with Mahavel reach, 11% for the lower part of Mahavel reach) and the obvious steepness of both Mahavel and Dimitile reaches compared to the Remparts River. The impact of the debris dam resulting from the 1965 collapse is still noticeable through the gentle slope upstream from the confluence. Also, the Remparts River upstream from the confluence with Mahavel reach was partially buried by a recent lava flow stemming from the Commerson crater (Billard and Vincent, 1974). This river bed is therefore partially “fossilized” and protected from rapid incision.

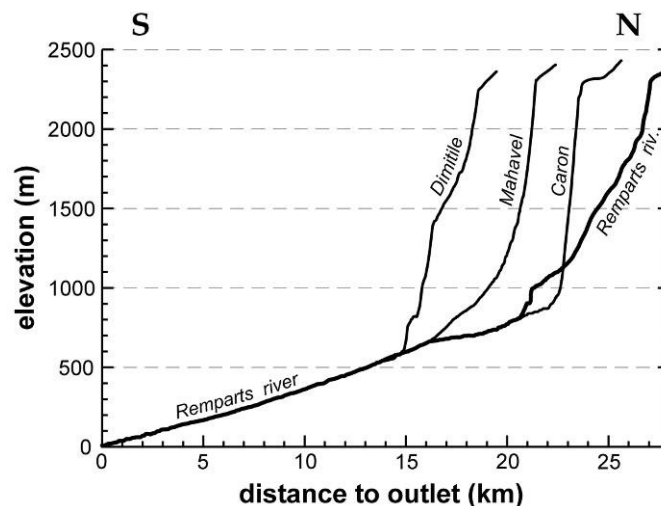


Figure 3. Longitudinal topographic profiles of Remparts River and tributaries (extracted from IGN 25-m DEM).

CLIMATOLOGY AND CYCLONIC SEQUENCE

Precipitation is high and variable, from 3000 to 4250 mm/yr over the watershed (average 1971 to 1994). Exceptional meteorological events can be responsible for huge rainfall. For instance, the upstream part of Remparts River (Commerson station) received 1575 mm of rain in 24 hours during cyclone Clotilda. During cyclone Firinga (1989), maximum intensity was reached on January 19th at 97 mm/hr (source of data: Météo France).

The observed lack of landscape evolution between two successive wet seasons shows that only intense and/or long periods of rainfall can shape the valley through the transport of coarse materials downstream. So, major cyclones and tropical depressions for the last 40 years have been reported in Figure 4 if total rainfall exceeds 300 mm and if one or both of the following criteria is reach:

The pluvial event has duration equal to or longer than 72 hours,

The average intensity of rainfall during the whole event is equal to or greater than 20 mm/hr.

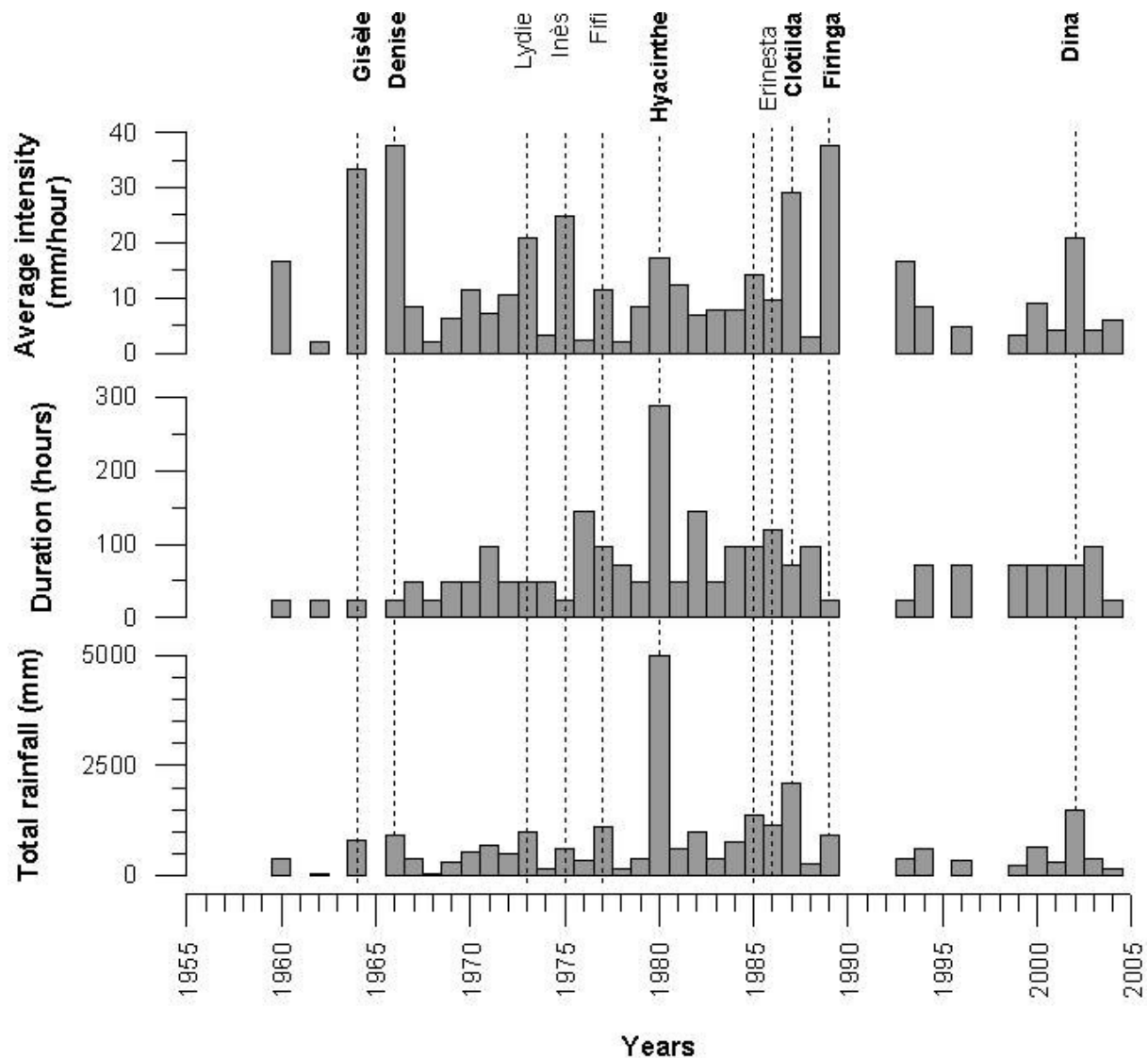


Figure 4. Climatological characteristics of main cyclonic events during the last 40 years (data from Météo France).

HYDROLOGY

Field measurement of flood discharge in such a cyclonic context is impossible, because heavy rains involve very fast and turbulent flows that prevent the use of any measurement device. Moreover, intensive sediment transport during floods would remove any instrumentation. For this reason, only estimations of flood discharge evaluated in the « Flood Protection Technical Scheme » (SOGREAH, 1992) using rational formula are available for the Remparts River. Runoff coefficients used here were : $C_{(T = 10 \text{ years})} = 0.6$, $C_{(T = 50 \text{ years})} = 0.75$, $C_{(T = 100 \text{ years})} = 0.80$.

Concentration time τ in the Remparts watershed is evaluated with Kirpich (1940) formula :
 $2.2 \text{ hours} < \tau < 3.8 \text{ hours}$.

Peak discharge estimation (Giandotti, 1940) at the outlet is presented in table 1.

Recurrence interval (years)	Peak discharge (m^3/s)	Specific discharge ($\text{m}^3/\text{s}/\text{km}^2$)
10	760	11.7
30	1040	16.0
100	1360	20.9

Table 1. Peak discharge estimation at the outlet of the Remparts River, according to recurrence interval (see explanations in the text).

MASS WASTING AT MAHAVEL CLIFF

Mass wasting events at Mahavel cliff can be rainfall triggered. Volcanic induced seismic activity is another potential triggering factor, however no link with instrumental seismicity has ever been observed at the seismological station located nearby.

Known major events

Mass wasting events involving a significant volume of material in a short time are called “major events” hereafter. A major event typically provides an amount of 1 million or so cubic meters in a few hours or a few days. Major events known to have occurred at the Mahavel Cliff during the last century are extracted from the French landslide database BDMvt (BRGM), and listed in Table 2.

Minor events : “background noise”

In addition to major collapse events, smaller mass wasting events frequently affect the Mahavel Cliff, essentially during the wet season. Although they are not comparable to major events, they happen frequently enough to provide significant volumes of material to the Mahavel reach, when considered over several decades. The French Geological Survey (BRGM) evaluated the volume of this “background noise” sediment supply to be $50\,000 \text{ m}^3/\text{yr}$ (M. Cruchet, pers. comm.). This volume represents a total over 40 years $2 \times 10^6 \text{ m}^3$, thus amounting to twice the 2001 major event.

Designation	Date	Volume ($\times 10^6 \text{ m}^3$)	Duration
1904	?	?	?
1965	6 May 1965	50	?
1996	9 Jan 1996	5	?
2001	8 to 18 Jan 2001	1	10 days

Table 2. Characteristics of major collapses at Mahavel Cliff (source: BDMvt database, BRGM).

TRANSPORT PROCESSES

The main effect of major and minor mass wasting events is to supply sediments from hillslopes to the valley bottom. Sediments provided by mass wasting are coarse and mainly consist of boulders (up to 1-2 m diameter), pebbles and gravel. Consequently, depending on the available power of transport, as well as on climate, main transport processes likely to carry such materials are: debris flows, lahars, hyperconcentrated flows, and bedload transport.

3.2. Functional analysis of the Remparts River and Mahavel reach

The recent evolution of the geomorphological system comprising the Mahavel Cliff, the Mahavel reach and the downstream Remparts River was analyzed through available climatic and morphological data. The first consist of the climatic sequence for the past 40 years, the latter consist of mass wasting events data (Table 2), a set of aerial photos (dated from 1961, 1966, 1978, 1984 and 1997, see an extract on Plate 1) and a SPOT5 image (dated from 2002). Together these data and field observations (Plate 2) allowed the detection of correlations between climatic events, mass wasting events and episodes of sediment transport. This analysis led us to the proposal of division of the Remparts River and Mahavel reach into in three compartments (Figure 2 and Plate 1), each one characterized by its behavior in response to three distinct types of geomorphological events (summarized in Table 3). Images which have helped develop this scheme are described in detail further in the text.

COMPARTMENTS

Compartment C1: primary sediments provider and primary tank

In this compartment, gravity processes are dominant and take place through various types of cliff collapses (Table 3), controlled by the intensity and the duration of cyclonic rains. Most of the blocks produced by the dismantling of the cliff are first stored in this sector, which is thus the primary tank for sediments. Only exceptional events such as in 1965 may directly transfer part of the debris supply from the cliff to the Mahavel reach and to the confluence. Apart from episodes of intense mass wasting, this compartment is affected by torrential processes contributing to the degradation of the hillslopes and the valley bottom. This segment is limited downstream by the “Oiseaux Verts” Cape (Figure 2).

Compartment C2: secondary tank – Mahavel reach

This compartment extends from the Oiseaux Verts Cape to the confluence with the Remparts River (Figure 2, Plate 2a). Surface processes operating in this compartment are of two types (Table 3):

- A - Gravity-driven processes such as large-scale cliff collapses (several tens of millions cubic meters); the whole area of the Mahavel reach can be buried under the products of the collapse (as in 1904 and 1965). Pre-existing depressions are filled with new sediments and the valley floor rises by, up to several tens of meters.
- B - Torrential processes; two functional modes are identified:
 - remobilization and transport by water of the sediments previously stored in C1, forming an alluvial fan. This process also raises the valley floor locally or across its entire width by filling pre-existing channels. Channel pattern is generally braided. Although

aggradation prevails, occurrence of debris flows may initiate new deeply incised channels, even if the sedimentary balance is positive (as for cyclone Dina in 2002).

- torrential bedload transport towards C3 through one or more channels. This process evolves the Mahavel reach towards a more dissected fluvial system. This erosional phase operates during each wet season if there is no major climatic or mass wasting event.

These processes are determined by:

- the occurrence or not of a significant mass wasting event,
- the volume of sediments stored in the primary tank (C1),
- intensity, amount and duration of precipitation (climatic control).

Compartment C3: Remparts River – sediment transfer to the ocean

This compartment is only affected by torrential processes, transporting materials downstream from the Mahavel reach (Table 3). Net aggradation and/or erosion depend on the balance between transport capacity and sediment yield (Plate 2b).

Sediment supply and water discharge are highly variable in time and space, in relation to the temporal scattering of mass wasting events and precipitation. The morphological evolution of C3 is thus very heterogeneous in time and space. Moreover, the sediment are very heterogeneous in size, the largest boulders and blocks can only be transported during intense peak discharge events. As a result, temporary armouring of the river bed may occur locally, as well as damming effects, thus enhancing the contrast between successive reaches (Gutierrez et al., 1998; Berti et al., 1999; Lisle and Church, 2002).

The confluence area may receive so much sediment that the bed of the river is obstructed by a dam. A lake may then appear upstream as occurred after the 1965 and 2002 events. Intense rainfall may cause the dam to break, leading to flash flooding and/or debris flow.

SEDIMENT TRANSFER EVENTS

Local geomorphological events can be grouped in three classes, according to their recurrence interval, duration and surface processes.

First class: Exceptional events

At the Mahavel Cliff, a major large-scale cliff collapse like the 1965 one causes almost immediate aggradation in C1, as well as in C2. The effect on C3 is a dam forming across the valley, creating a lake upstream. This type of event will occur with a frequency of few times a century. Characteristic duration ranges from seconds to several hours. Such historic events occurred in 1904 (according to oral records) and 1965 (BRGM, 1965).

Second class: Major events

Large transfer of sediments from C1 to C2 occurs mainly through debris flows and hyperconcentrated flows. A part of the available material of C2 is eroded and transported through torrential and fluvial processes towards the Remparts River, which carries it downstream. The occurrence of major events depends on the duration and intensity of rains during the cyclone season. In 2002, because cyclone Dina followed the 2001 mass wasting event (Figure 4, Table 2), the large volume of available sediments stored in C1 led to a significant positive sediment budget in C2. The river bed of Mahavel reach thus experienced massive aggradation. A major event will occur between one and several times per decade. Characteristic duration is several hours to several days.

Third class: “normal” events

Normal events occur each wet season but can be erased by a violent cyclone. Moderate torrential processes allow sediment transfer from C1 to C2. This bedload transport implies

fresh fluvial incision in the hydrographic network. In C2, a well-channelized network develops. Previous deposits are evacuated downstream into the Remparts River and then progressively migrate through C3. This heterogeneous migration depends on local hydraulic and hydrological conditions (Lisle and Church, 2002). Some reaches may be aggrading while others are incised. The granulometry of river bed sediments is an important factor of morphological processes. In fact, blocks and boulders are only transported during major infrequent floods. Most of the time, only finer sediments are transported and bed armouring progresses until a major event occurs. Normal events have an annual frequency, occurring during each wet season. Characteristic duration is a few days to a few months.

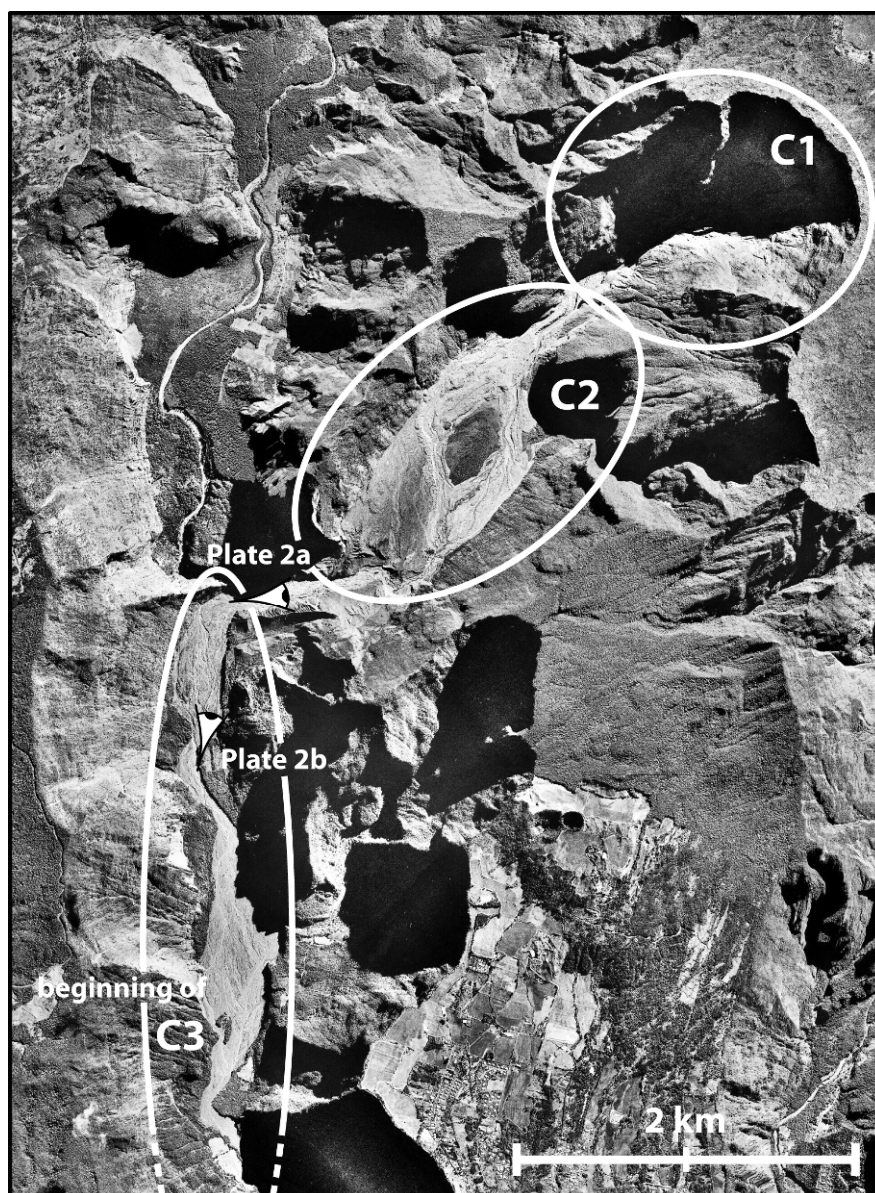


Plate 1. Aerial view (1997 orthophoto) of the confluence between the Mahavel reach and the Remparts River, helping to distinguish the three compartments of the “active” hydrosystem (eyes correspond to points of view for plate 2).

(a)



(b)

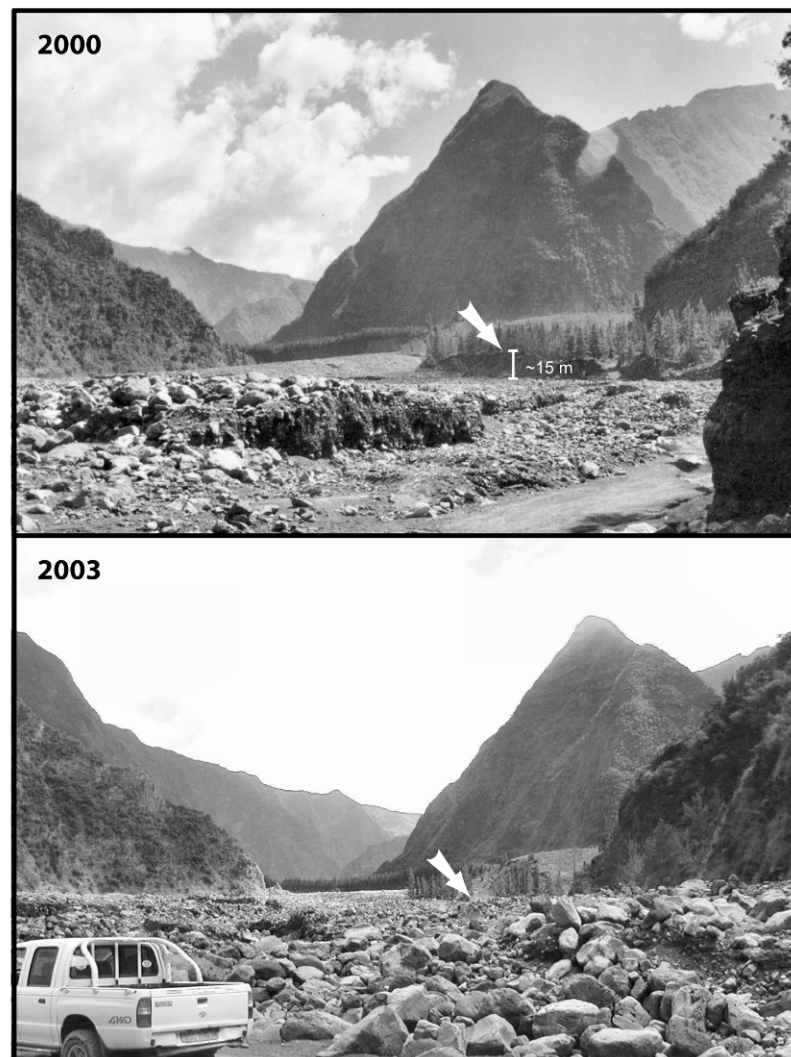


Plate 2. Field photographs: a. view of the Mahavel reach, towards upstream (2003); b. view of the left bank of the Remparts River, where a terrace (white arrow) disappeared between 2000 and 2003.

Table 3. The different functional compartments of Remparts river and Mahavel reach, and their response to different possible geomorphological events (type of dominant processes for each compartment is in italic).

Main function	Location	Type of processes	Processes	Type of event	Effects	
First Compartment (C1)	Main sediments provider and primary tank	Mahavel Falaise and funnel as far as “Oiseaux Verts” Cape	Mass wasting	Cliff collapse and landslides	Exceptional event	Material supply to and storage in C1 and C2
			Torrential	Debris flows	Major event	Material supply to C2
				Bed load transport	Normal	Material supply to C2
Second Compartment (C2)	Secondary tank	Mahavel reach	Mass wasting	Landslides	Exceptional event	Material storage in C2
			Torrential	Debris flows	Major event	Aggradation / degradation of C2 and material transfer to C3
				Bed load transport	Normal	Aggradation / degradation of C2 and material transfer to C3
Third compartment (C3)	Transfer of sediments	Downstream from Mahavel reach	Torrential	Debris flows	Major event	Aggradation in C3
				Bed load transport	Normal	Degradation and transfer to ocean

4. Observation of the river evolution during the last 40 years

Geomorphic mapping using aerial photographs and a satellite image acquired over the past 40 years illustrate the proposed functional analysis. The 1997 orthophoto (1 m resolution) allowed us to reference the 1961, 1966, 1978 and 1984 images (5 m resolution) with ground control points on the river bed. The SPOT5 multispectral orthoimage was acquired in 2002, with a 2.5 m resolution. Plates 3 and 4 show the evolution of C2 and C3 respectively, from 1961 to 2002. Plate 5 refers to C3 further downstream. Important features are labelled with small letters.

Plate 3 shows that in 1961, an active channel is eroding through an old morphological surface, probably resulting from a former exceptional event ("a" and "b"). According to oral sources, massive sediment supply occurred in 1904. Following the exceptional Mahavel event that occurred in 1965, around $50 \times 10^6 \text{ m}^3$ of rock collapsed from the cliff into C1. A part of this huge volume immediately slid into C2, reached the confluence and dammed the river. A few months later, cyclone Denise hit Reunion Island, causing intense precipitation (Figure 4, BRGM, 1966). Consequences of this succession of events may be observed on the 1966 aerial view. This photo shows evidences of the passage of an enormous wave of sediments through the reach, which likely burst as it collided with the stiff spur at the confluence. White deposits on the right side of the reach and much further upstream (1966, "c") may be remnants of splashes of fine sediments. Former channel "b" has been filled in, and a drift of fresh sediments now deviates the channel further north (1966, "e"). Fresh sediments cover the whole surface of the reach. In particular, the former bed of a braided channel "a" has completely vanished beneath the new sediment layer. The reach surface rises further during following years, as observed near "d", and generally across all of the upper part of the reach (1978). During the same period, the drift "b" underwent erosion, that is still going on. At the confluence, regressive erosion also appears to remove the northern part of the 1965 deposits (1978, "e"). The dam of the river upstream, which resulted from the 1965 event, remained intact until between 1984 and 1997 ("f"). A major event occurred in 1996, supplying around $5 \times 10^6 \text{ m}^3$ of rock material to C1. Consecutive debris flows through the reach renewed the surface on the left side (1997, "g"). Labels "h" and "i" (1997, 2002) indicate a levee of solidified mud, testifying to the passage of debris flow in the reach, which likely happened in 1996. Sediment supply from C1 gradually fed C2, as the surface texture of the reach seems to indicate further burying between 1997 and 2002 ("g", "h" and "j").

Plate 4 shows the Remparts River just downstream of its confluence with the Mahavel reach. Sediment drift ("a") resulting from the Mahavel event and subsequent erosion can be recognized. At location "b", a preexisting channel less than 100 m wide in 1961 is partly filled by 1966, leading to the 400 m valley bottom being fully covered by sediments between 1966 and 1978. Further downstream meander "c" is also buried during this period. After 1978, the 400 m wide sediment-covered river bed is partially abandoned, thus forming a terrace ("d"). The terrace edge retreats towards the East between 1984 and 1997, because of local erosional activity of the river. In the same period, sediment supply leads to valley infilling and burying of vegetated banks downstream ("e" and "f"). This material may come from either local erosion upstream or sediment transfer from C2. Afterwards, a new sedimentation phase affects the whole river reach, in response to the 1996 major event. Terraces "d" and "g" are submerged beneath fresh sediments (see also Plate 2b), as the valley infill thickens at locations "e" and "f".

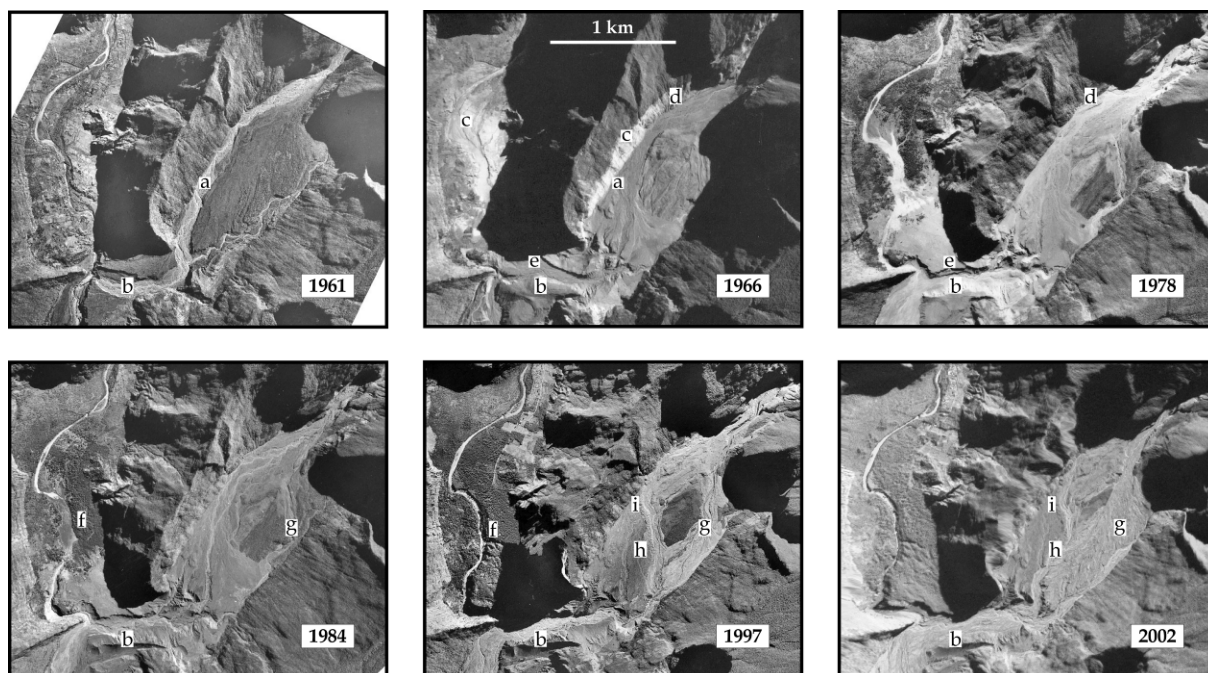


Plate 3. Remparts River evolution on aerial photographs (1961 to 1997) and SPOT5 image (2002), focused on Mahavel reach and confluence with Remparts River (see location on figure 2).

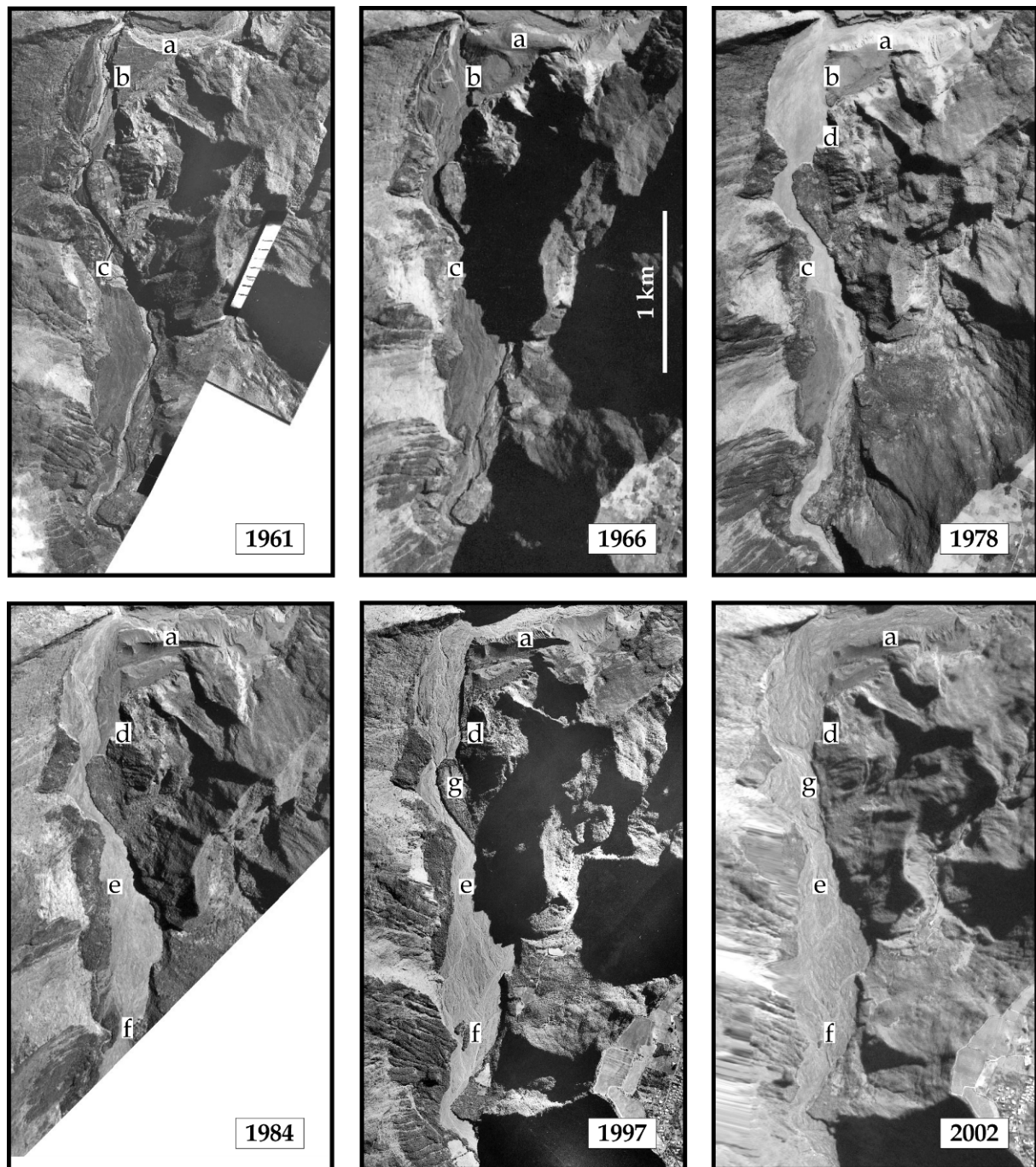


Plate 4. Remparts River evolution on aerial photographs (1961 to 1997) and SPOT5 image (2002), focused on the area downstream of confluence with the Mahavel reach (see location on figure 2).

Plate 5 shows sediment transfer further downstream in the river (C3, not covered by the 1961 flight). Islets (local term for small islands) in the valley bottom which were still vegetated in 1978 (“a” and “b”) have been progressively submerged by sediment supply from upstream, until becoming barely visible on the 2002 image.

The most remarkable observation about the morphological evolution of C2 and C3 is that the valley bottom seemed to be recently filled with new sediments, especially on the 1978 and 2002 images. Nevertheless, the main events of sediment supply occurred in 1965 and 1996, without notably affecting the morphology on the 1966 and 1997 images. This delay illustrates the response time of sediment transfer following a big sedimentary pulse from a cliff collapse

in C1. While the sediment supply is mainly due to collapse and landslide events, sediment transfer occurs because of high magnitude rainfall events. The progress of material downstream of the source thus depends on the meteorological sequence. The largest rise in the river bed can be observed on the 2002 image, as a likely consequence of cyclone Dina. None of the earlier photos shows such a rapid sedimentation

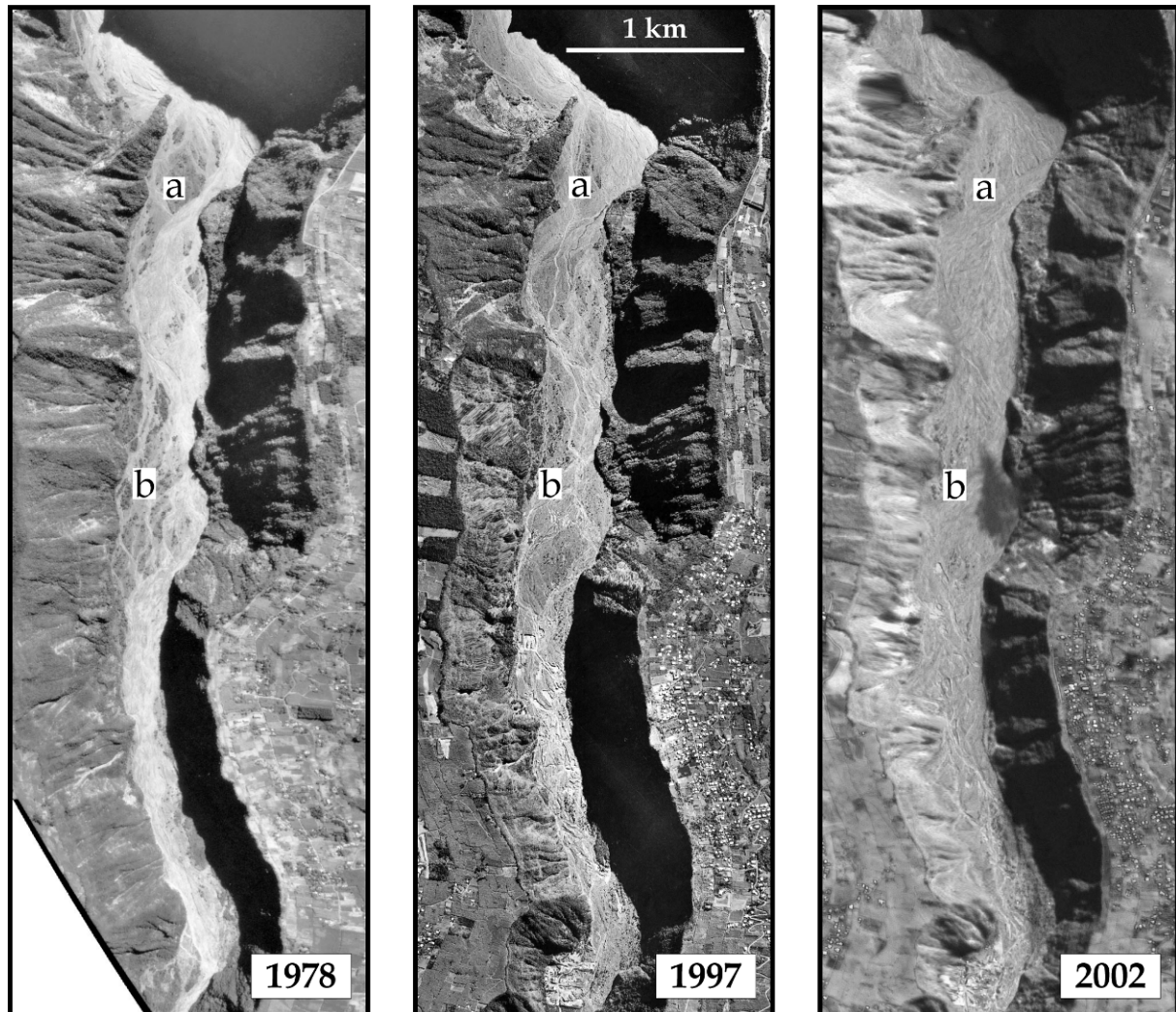


Plate 5. Remparts River evolution on aerial photographs (1978 and 1997) and SPOT5 image (2002), focused on the downstream part of Remparts River (see location on figure 2).

5. Quantification of volumetric variation of sediments within the river bed (1997-2002)

Geomorphological analysis of the 2002 SPOT image shows that the passage of cyclone Dina over the Remparts watershed corresponds to a major event. Although no large-scale collapse of Mahavel Cliff occurred, the effects on the morphology are significant. Two distinct topographical datasets are used to estimate the change in bed elevation induced by the passage of such a cyclone. The first dataset is the 2000 update of the IGN (Institut Géographique National) topographical data base, based on 1997 field measurements and aerial photos. Displayed horizontal resolution of this data is 0.75 m. The second dataset consists of theodolite measurements of the river bed acquired by the DDE (Direction Départementale de l'Équipement) in 2002. These two topographical datasets bracket the passage of cyclone Dina in January 2002.

Both datasets come in the form of contour lines, at 10 m intervals for the 1997 dataset and at 1 m intervals for the 2002 dataset. The spatial distribution of 2002 point measurements is very dense, as the aim was an accurate description of river bed. All intersections between the respective sets of contour lines were identified thus obtaining a direct estimation of the variation in elevation between 1997 and 2002 on 764 points. This set of points was then sorted by hand to remove points located on the border of the 2002 data acquisition, where the spacing of 1997 contour lines is too large to accurately fit the bottom of the bordering cliff. A surface was interpolated from the retained points, with a cell size of 5 m, using the ArcGIS software (Figure 5). Tests were carried out on a number of interpolation schemes (inverse distance weighted, spline and kriging methods), and the natural neighbor interpolation was selected, as the generated surface interpolated was most realistic. The resulting map of 1997-2002 differential elevation was used to compute local sediment budgets over this period. The study area was split in 4 distinct zones (Figure 5), in order to identify the part of the river most affected by cyclone Dina. Concerned surfaces and estimated sediment volumes are reported in Table 4. Results obtained using the other surface interpolation methods provided similar quantification of volumes to within about 5%.

River bed topographical variation between 1997 and 2002 ranges from -18m to $+22\text{m}$. The global volume of sediment deposition on the study area reaches $8.9 \times 10^6 \text{ m}^3$, compared to an eroded volume of $0.85 \times 10^6 \text{ m}^3$. Eroded zones mainly correspond to places where fluvial incision or bank erosion prevails. Zone 1 especially, which covers the measured part of Mahavel Reach, corresponds to 41% of total eroded sediments, for a surface area of only 9% of the total area studied. On the contrary, the biggest volume of aggraded sediment border the confluence, and zones 1 and 2 correspond thus to 61% of total aggraded sediments, as they only cover 20% of total area. Erosion is almost not noticeable in zone 3, but still affects notably zone 4, the most downstream part of C3. Uncertainty on these volume estimations is very difficult to evaluate, as the uncertainty associated with the topographic data is unknown. However, comparison between several methods of surface interpolation show that uncertainties on volume estimations should not exceed 10%.

Unfortunately, the 2002 data do not cover the upstream part of Mahavel reach. Therefore, the differential volume between 1997 and 2002 is underestimated. Indeed, observation of 1997 aerial photo and 2002 SPOT image as well as field controls (2000, 2003) clearly show that important sediment deposition occurred in the Mahavel reach between 1997 and 2002.

Zone	ΔZ_{min} (m)	ΔZ_{max} (m)	relative area (%)	AGGRADATION	Area ($\times 10^5 \text{ m}^2$)	Volume ($\times 10^6 \text{ m}^3$)	relative volume (%)	EROSION	Area ($\times 10^5 \text{ m}^2$)	Volume ($\times 10^6 \text{ m}^3$)	relative volume (%)
all	-18	22	-		2.67	8.9	-		0.59	0.85	-
1	-18	22	9		0.21	2.0	22		0.09	0.35	41
2	-6	22	11		0.33	3.5	39		0.03	0.05	6
3	-3	9	33		1.01	2.0	23		0.06	0.03	3
4	-6	5	47		1.12	1.5	16		0.41	0.42	50

Table 4 : Estimated sediment budget for zones 1 to 4 (see location on figure 5); ΔZ is the variation in elevation between 1997 and 2002

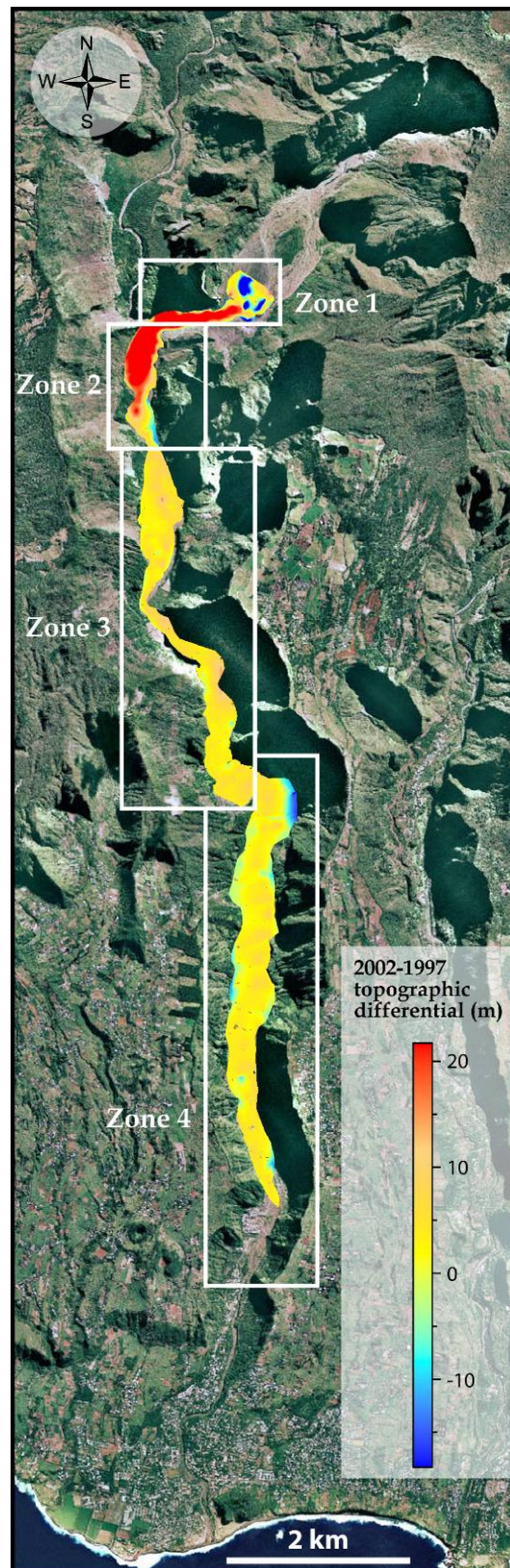


Figure 5. Map of interpolated differential topography between 1997 and 2002, superimposed to 1997 aerial orthophoto of the Remparts watershed. The area of calculation is splitted in 4 zones, a sediment budget being estimated for each (see table 4).

FIELD ANALYSIS AND VALIDATION

Field work and geomorphological mapping was carried out in 2000 and 2003 (thus bracketing cyclone Dina). Comparison between field observations and geomorphological maps (Garcin and Cruchet, 2001) allows *in situ* verification of major evolution and aggradation of the river bed. This aggradation is highly noticeable as numerous vegetated low terraces which were present in 2000 are now buried by several meters of alluvium (Plate 2b). As an example, the Grand Ilet Terrace (downstream of the Mahavel-Remparts confluence, label "g" on plate 4) which was settled until the 1990's has been submerged by sediment even though this islet had been preserved from the 1965 event. Further downstream, a few lateral terraces are today settled and are threatened by aggradation. A coarsening of the river bed sediment is observed between 2000 and 2003 along the whole length of the bed. The only source of material is the Mahavel reach, as the upstream part of the Remparts River supplies no sediment and no landslide is observed in the bordering cliff. The sediment source is mainly C1, but some is produced from river incision in the surface of C2. This incision is clearly visible both in the field and on the aerial photographs (Plates 2a and 3).

6. Discussion and conclusions

Sediment dynamics in the Remparts River is complex and does not follow a continuous linear evolution. Systemic analysis and retrospective study show a step-like evolution. This evolution is characterized by the occurrence of morphogenetic events of various magnitudes and frequencies, triggered by heavy tropical rainfalls and determined by prior conditions in the different compartments. Geomorphic consequences of exceptional collapses at Mahavel Cliff are not immediate but extend over decades. During the past decades, the different river reaches were not necessarily affected by the same evolutionary trends of deposition, incision and stability.

Similar dynamics of steplike sediment transfer may be observed in case of smaller storm-induced debris flow events in an Alpine context (Berti et al., 1999). During the cyclone Dina in 2002, all reaches have been aggrading except the reach furthest downstream. The bed elevation of the Remparts River is now higher than ever observed. This overall aggradation of the river bed corresponds to a release of $8.9 \times 10^6 \text{ m}^3$ of sediment spread on a 11 km long river reach. The area of confluence between Mahavel reach and the Remparts River corresponds to only 20% of the river bed surface, but contributes 50% of the volume of aggraded sediment. One can expect massive aggradation of the downstream part of the river over the next years. The reach of the river located furthest downstream and consisting of narrow gorges is not yet affected by significant aggradation. It indicates that this section is not yet in equilibrium with the upstream reaches. These gorges need around $700\,000 \text{ m}^3$ of alluvium to be submerged by sediment, corresponding to only $1/10^{\text{th}}$ of the estimated volume released by cyclone Dina. The rapid infill of the gorges is thus possible in case of major cyclones in the future with potentially disastrous consequences for the city of Saint-Joseph.

This first attempt of quantification of sediment budget shows that even without exceptional mass wasting event in the Mahavel Cliff, a huge volume of sediment can be released and cause aggradation of a significant part of the Remparts River. The estimated volume of transported sediment corresponding to a very short period (a few hours to a few days) with regard to geological time reveals the high landscape evolution rates on Reunion Island. Geomorphological analysis indicates local high velocity processes of mechanical erosion not revealed by studies using a geochemical approach (Louvât and Allegre, 1996, 1997). Estimation of sedimentary budget also confirms that both cyclonic and volcanic contexts make surface processes very rapid, in comparison with less extreme conditions. For example, the estimated transport rate amounts to around 10^3 times that estimated in a study of a mountainous, storm-fed river in British Columbia (Martin and Church, 1995).

However, a similar event of massive rainstorm triggered debris flows was observed in Venezuela in December 1999 (Wieczorek et al., 2001). Although the depositional volume of

sediments estimated by Wieczorek et al. (2001) concern an alluvial fan and not a river, one can compare the $1.8 \times 10^6 \text{ m}^3$ of deposits to the $8.9 \times 10^6 \text{ m}^3$ of aggraded sediments in the Remparts River. Compared to former worldwide debris flows reported by Wieczorek et al. (2001), the debris flow event triggered by cyclone Dina in 2002 in the Remparts River thus appears to be one of the largest debris flows on record worldwide.

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