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Feedback (2024-2025) on flood risk in Réunion Island (France, Indian Ocean): From the analysis of temporal and spatial dimensions to the implementation of mitigation strategies

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ABSTRACT

This paper aims to assess flood risk in Réunion Island, taking into account historical data as well as the recent impacts of cyclones Belal (2024) and Garance (2025). It seeks to demonstrate that solutions grounded in a hydro-geomorphological approach can effectively mitigate flood risk, notwithstanding the challenges posed by increasing urbanisation in valley floors. Volcanic in origin, Réunion Island is situated in the Indian Ocean, approximately 678 km east of Madagascar. Its mountainous landscape and subtropical climate make its hydrographic network particularly dynamic, leaving its inhabitants vulnerable to extreme hydrometeorological events, thereby contributing to a heightened flood risk. The study employs a multidisciplinary approach, integrating historical data (inclusive of texts, maps, and photographs) alongside field data (encompassing geomorphology, stratigraphy, hydraulics, and land use). The findings reveal historical settlement patterns across four types of geomorphological units: 'planèzes', slopes, valley floors, and coastal plains. Presently, the rivers are not adequately managed to address the hydro-geomorphological dynamics, which include the need for discharging substantial volumes of water and sediment through channels of appropriate capacity, lateral migration of sinuous channels, channel avulsions, and the incorporation of stormwater runoff into river flows. Alarmingly, 61 % of the population residing in valley floors are at risk of flooding. The discussion highlights the ineffectiveness of current flood-control strategies, which have inadvertently exacerbated vulnerability. It underscores the urgent necessity for an integrated approach to flood-risk management, incorporating dynamic hydro-geomorphological mapping and an enhanced sensitivity to the ramifications of climate change. Raising community awareness and reducing vulnerability through improved regulation and planning are crucial steps to address the challenges that lie ahead.

Keywords: Réunion Island, flood risk, fluvial geomorphology, space-time analysis, mitigation strategies.

RÉSUMÉ

Cet article vise à évaluer le risque inondation sur l'île de La Réunion, en tenant compte des données historiques et des impacts récents des cyclones Belal (2024) et Garance (2025). Il cherche à démontrer que des solutions basées sur une approche hydro-géomorphologique peuvent réduire le risque inondation, malgré les défis liés à l'urbanisation croissante dans les fonds de vallée. La Réunion est une île volcanique située dans l'océan Indien, à 678 km à l'est de Madagascar. Sa topographie montagneuse et son climat subtropical rendent son réseau hydrographique particulièrement dynamique et ses habitants vulnérables aux événements hydrométéorologiques extrêmes, ce qui contribue à un risque inondation élevé. L'étude mobilise une approche pluridisciplinaire, intégrant des données historiques (textes, cartes et photographies) et de terrain (géomorphologie, stratigraphie, hydraulique, occupation du sol). Les résultats montrent une installation historique sur quatre types d'unités géomorphologiques : planèzes, versants, fonds de vallée, plaine côtière. Les rivières ne sont pas aménagées pour parer à la dynamique hydro-géomorphologique des rivières que sont : de très forts débits liquides et solides à évacuer dans une section de chenal suffisante ; la migration latérale des chenaux sinueux ; les défluviations ; l'intégration du ruissellement pluvial aux eaux fluviales. 61 % de la population vivant dans les fonds de vallée est exposée au risque inondation. La discussion aborde l'inefficacité des stratégies d'endiguement qui ont aggravé la vulnérabilité. Elle souligne l'urgence d'une gestion intégrée du risque inondation, incluant une cartographie hydro-géomorphologique dynamique et une sensibilité accrue aux impacts du changement climatique. La nécessité d'une sensibilisation communautaire et d'une réduction de la vulnérabilité par une meilleure réglementation et planification est essentielle pour contrer les défis futurs.

Mots-clés : *île de La Réunion, risque inondation, géomorphologie fluviale, analyse de l'espace-temps, stratégies d'atténuation.*

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1. Introduction

While the French school of fluvial geomorphology has yielded a substantial body of literature, it is evident that French rivers have predominantly been studied within metropolitan France (fig. 1). Undoubtedly, a considerable amount of hydro-geomorphological expertise informs local infrastructure; however, comparatively few studies have been published concerning the watersheds of overseas territories (Bravard et al., 2001; Lorion, 2006; Stumph et al., 2016). In the context of rivers draining these overseas watersheds, particularly on volcanic islands, three distinctive features warrant thorough investigation: firstly, these are primarily tropical, high-energy rivers (ω > 300 W/m^2), which pose significant management challenges in terms of hydrology and coarse sediment transport (Pardé, 1957; Barcelo et al., 1997; Lavigne and Thouret, 2003; Galewsky et al., 2006; Ikhsan et al., 2019; Allemand et al., 2023; Gonzalez et al., 2023; Baby et al., 2024; Folton, 2024; Gayer et al., 2025); secondly, these rivers necessitate the adaptation of management strategies in light of the increasing frequency of high-intensity hydrometeorological events (Gurung et al., 2021; Dumont et al., 2023; Fort et al., 2025; Tolentino et al., 2025); and thirdly, ongoing climate change could further exacerbate the frequency and intensity of hydrometeorological hazards (IPCC, 2023).

The rivers of the Réunion Island fit perfectly into this scientific conceptual framework. While flood prevention falls under the purview of an agency that coordinates and supports local GEMAPI (Management of aquatic environments and flood prevention) communities, the DEAL – Directorate for the environment, planning, and housing (*https://www.reunion.developpement-durable.gouv.fr/*) demonstrates remarkable effectiveness in flood prevention. This effectiveness is complemented by its successful facilitation of dialogue among the various institutional partners and stakeholders involved in risk management. However, Réunion Island has never been more populated, which means it is potentially more exposed to flood risk than ever before. This heightened risk persists despite the fact that river management projects have been underway for several decades (Lorion, 2006), and housing development continues to expand into valley floors (Amri, 2025).

This paper aims to assess flood risk in Réunion Island in light of the impacts of the two most recent cyclones that have struck the island: Belal (15 January 2024; four fatalities, plus an additional four deaths during the heavy rains at the end of January; 'Cat Nat' damage estimated between €20 million and €25 million), and Garance (28 February 2025; five fatalities; 68,000 reported claims with €379 million in 'Cat Nat' damage). This assessment is supported by field surveys that will help to contextualise recent events within a centuries-long timeline, thereby providing perspective on the associated risks. We aim to demonstrate that viable, common-sense solutions, grounded in a hydro-geomorphological and systemic approach at the watershed scale, do indeed exist to prevent or mitigate future disasters in valley floors. Despite the very limited potential for change (redevelopment) arising from the numerous hydro-geomorphological mismanagement issues that occurred during the latter half of the 20th century – issues that are incompatible with urban development (Lorion, 2013) – it remains possible to integrate key physical and societal criteria to reduce the area at risk in the valley floors of Réunion Island.

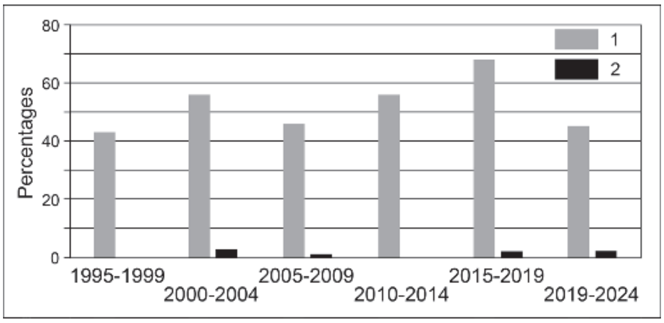


Fig. 1 – National and international bibliometric analysis of research papers (n = 322) published on rivers (processes, risks, restoration) between 1995 and 2024, analysed in 5-year intervals distinguishing (1) the mainland from (2) overseas territories. French journals consulted, in alphabetical order: Collections ÉDYTEM; Géocarrefour; Géomorphologie: relief, processus, environnement; Norois; Physio-Géo; Quaternaire. International publishers: Elsevier; Wiley. Scientific productions concerning overseas territories account for barely 2.5 % of the total publications.

Fig. 1 – Analyse bibliométrique nationale et internationale des articles de recherche (n = 322) parus sur les rivières (processus, risque, restauration) entre 1995 et 2024, par tranche de 5 ans, en distinguant (1) la métropole (2) des territoires d'outre-mer. *Revues françaises consultées, par ordre alphabétique : Collections ÉDYTEM ; Géocarrefour ; Géomorphologie : relief, processus, environnement ; Norois ; Physio-Géo ; Quaternaire. Éditeurs internationaux : Elsevier ; Wiley. Les productions scientifiques concernant les territoires d'outre-mer atteignent à peine 2,5 % du total des parutions.*

2. Study area

Situated in the Southern Hemisphere, between the Equator and the Tropic of Capricorn, in the southwestern Indian Ocean, approximately 678 km east of Madagascar, Réunion Island is a French overseas territory that, alongside Mauritius and Rodrigues, forms part of the Mascarene Islands. The island is elliptical in shape and elongated from northwest to southeast, covering an area of 2512 km² with a maximum length of 71 km (fig. 2).

Réunion Island is characterised by its volcanic, mountainous, and tropical landscape (CNRS/IGN, 1975). Two volcanic massifs are situated side by side (Gillot et al., 1994; Lénat et al., 2001): in the northwest, the older (ranging from 2.1 million to 12,000 years ago) and larger (accounting for two-thirds of the total area) is a dormant volcano, with a topography significantly eroded over time, featuring the island's highest peak, Piton des Neiges (3070 m). In contrast, the more recent Piton de la Fournaise (2631 m), located in the southeast and active since approximately 0.53 million years ago, is a basaltic shield volcano with a gentler topography, as erosion has had less impact on its original morphology due to the shorter time scale of its activity. Since the period of permanent colonisation beginning between 1638 and 1646, 95 % of Piton de la Fournaise's eruptions have taken place within the Enclos Fouqué caldera (Villeneuve and Bachelery, 2006). The two mountain ranges are separated by two plateaus oriented northeast-southwest: the Plaine des Palmistes and the Plaine des Cafres. The topography of Réunion Island is notably rugged, with steep slopes that leave limited space for the development of plains, which are largely confined to the coastal areas. The island's interior is intricately carved by the three cirques of Mafate, Cilaos, and Salazie. These roughly circular depressions, spanning tens of kilometres, are the result of the subsidence of the magma chambers

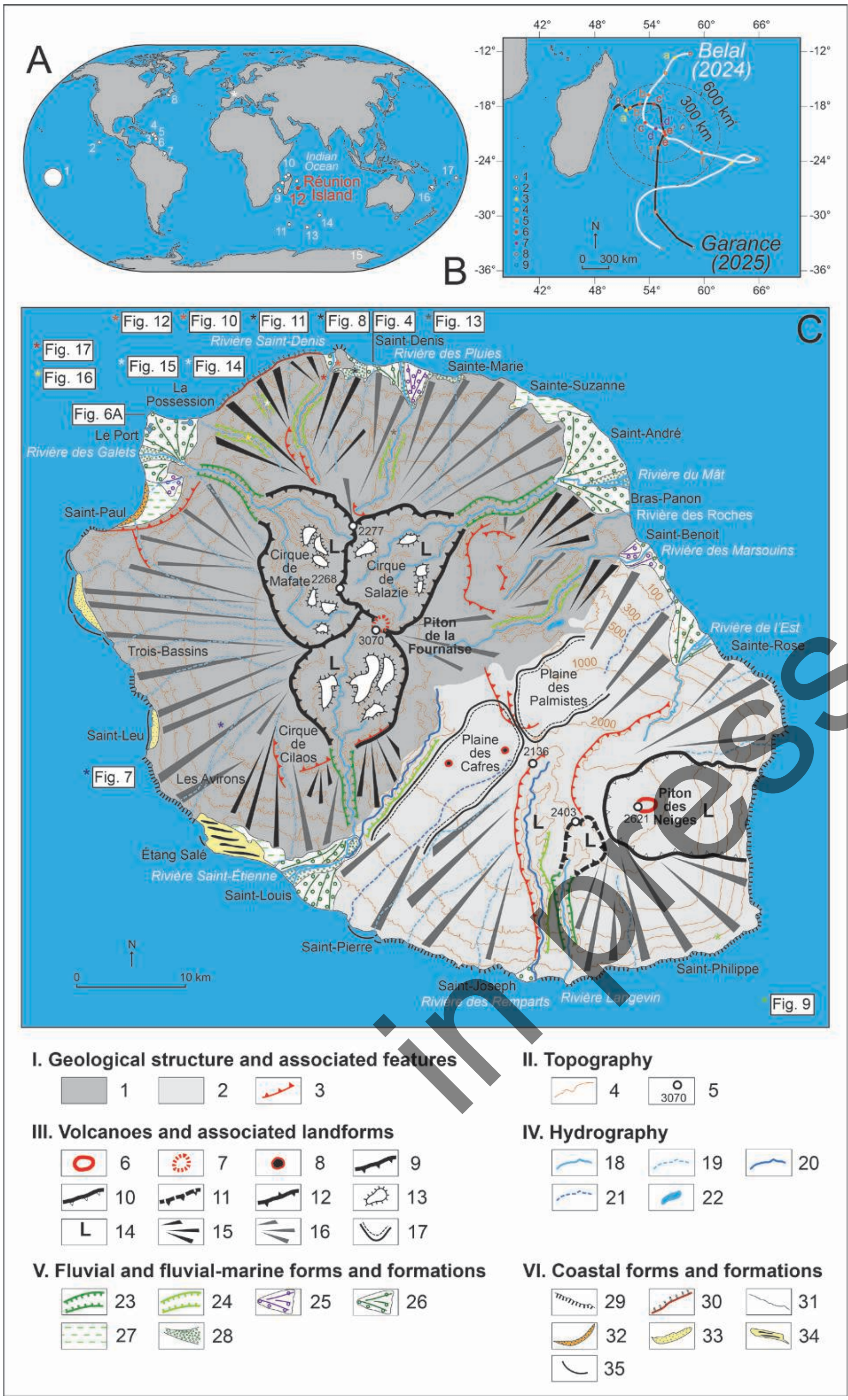


Fig. 2 – The Réunion Island.

A- location in the Indian Ocean and among France's overseas territories.

1- French Polynesia, 2- Clipperton, 3- Saint Barthélemy, 4- Saint Martin, 5- Guadeloupe, 6- Martinique, 7- French Guiana, 8- Saint Pierre and Miquelon, 9- Scattered Islands, 10- Mayotte, 11- Crozet, 12- Réunion, 13- Kerguelen, 14- Saint-Paul and New Amsterdam, 15- Adélie Land, 16- New Caledonia, 17- Wallis and Futuna. * Metropolitan France + Corse.

B- trajectory of cyclones Belal (2024) and Garance (2025).

1- yellow pre-alert on January 12 at 1 p.m. (local time). 2- orange alert on January 13 at 7 p.m. (local time), 3- red alert on January 14 at 8 p.m. (local time), 4- purple alert on January 15 at 6 a.m. (local time), 5- return to red alert on January 15 at 1 p.m. (local time), 6- return to orange alert on January 16 at 12 p.m. (local time). a- yellow pre-alert on February 24 at 7 p.m. (local time). b- orange alert on February 26 at 2 p.m. (local time), c- red alert on February 27 at 7 p.m. (local time), d- purple alert on February 28 at 9 a.m. (local time), e- return to red alert on February 28 at 12 a.m. (local time), f- return to orange alert on February 28 at 4 p.m. (local time). 1- depression, 2- tropical disturbance/Disturbed area, 3- tropical depression, 4- Moderate tropical storm, 5- severe tropical storm, 6- tropical cyclone, 7- intense tropical cyclone. 8- starting point, 9- end point.

C- Geomorphological map (modified from Cadet, 2003, and Sellier, 2016).

1- "Piton des Neiges" volcanic system, 2- "Piton de la Fournaise" volcanic system, 3- fault escarpment, 4- contour line (in m a.s.l.), 5- elevation point (in m a.s.l.), 6- central cone and active crater, 7- ancient crater, 8- maar, 9- circular caldera rim and cirque, 10- semi-circular caldera rim (+ landslide), 11- rim and cirque emerging through erosion, 12- intercalary ridge, 13- intra-caldera "îlet" and hill, 14- major landslide, 15- ancient volcanic plateau ("planèze"), 16- recent volcanic plateau ("planèze"), 17- high plain (erosion feature at the junction between the two volcanic edifices), 18- flank watercourse (major river = "rivière"), 19- flank watercourse (secondary river), 20- adjacent watercourse (major river = "rivière"), 21- adjacent watercourse (secondary river), 22- lake, 23- connecting gorge, 24- undifferentiated gorge, 25- ancient delta cone, 26- recent delta cone, 27- undifferentiated fluvial-marine accumulation plain, 28- braided active channel (before river embankment), 29- active cliff, 30- dead cliff (aligned with a fault escarpment), 31- undifferentiated low coast, 32- pebble beach (exposed to strong swells), 33- beach "relatively" protected from strong swells, 34- beach reshaped into wind-blown dunes, 35- coral reef.

Fig. 2 – L'île de La Réunion.

A : localisation dans l'océan Indien et parmi les territoires d'Outre-Mer de la France.

*1- Polynésie française, 2- Clipperton, 3- Saint-Barthélemy, 4- Saint-Martin, 5- Guadeloupe, 6- Martinique, 7- Guyane, 8- Saint-Pierre-et-Miquelon, 9- Îles éparses, 10- Mayotte, 11- Crozet, 12- La Réunion, 13- Kerguelen, 14- Saint-Paul et Nouvelle Amsterdam, 15- Terre Adélie, 16- Nouvelle-Calédonie, 17- Wallis-et-Futuna. * France métropolitaine + Corse.*

B : trajectoire des cyclones Belal (2024) et Garance (2025).

a- pré-alerte jaune le 12 janvier à 13 h (heure locale). b- alerte orange le 13 janvier à 19 h (heure locale), c- alerte rouge le 14 janvier à 20 h (heure locale), d- alerte violette le 15 janvier à 6 h (heure locale), e- retour à alerte rouge le 15 janvier à 13 h (heure locale), f- retour à alerte orange le 16 janvier à 12 h (heure locale). a'- pré-alerte jaune le 24 février à 19 h (heure locale). b'- alerte orange le 26 février à 14 h (heure locale), c'- alerte rouge le 27 février à 19 h (heure locale), d'- alerte violette le 28 février à 9 h (heure locale), e'- retour à alerte rouge le 28 février à 12 h (heure locale), f'- retour à alerte orange le 28 février à 16 h (heure locale). 1- dépression, 2- perturbation tropicale / zone perturbée, 3- dépression tropicale, 4- tempête tropicale modérée, 5- forte tempête tropicale, 6- cyclone tropical, 7, cyclone tropical intense. 8- point de départ, 9- point d'arrivée.

C : carte géomorphologique (modifiée de Cadet, 2003 et Sellier, 2016).

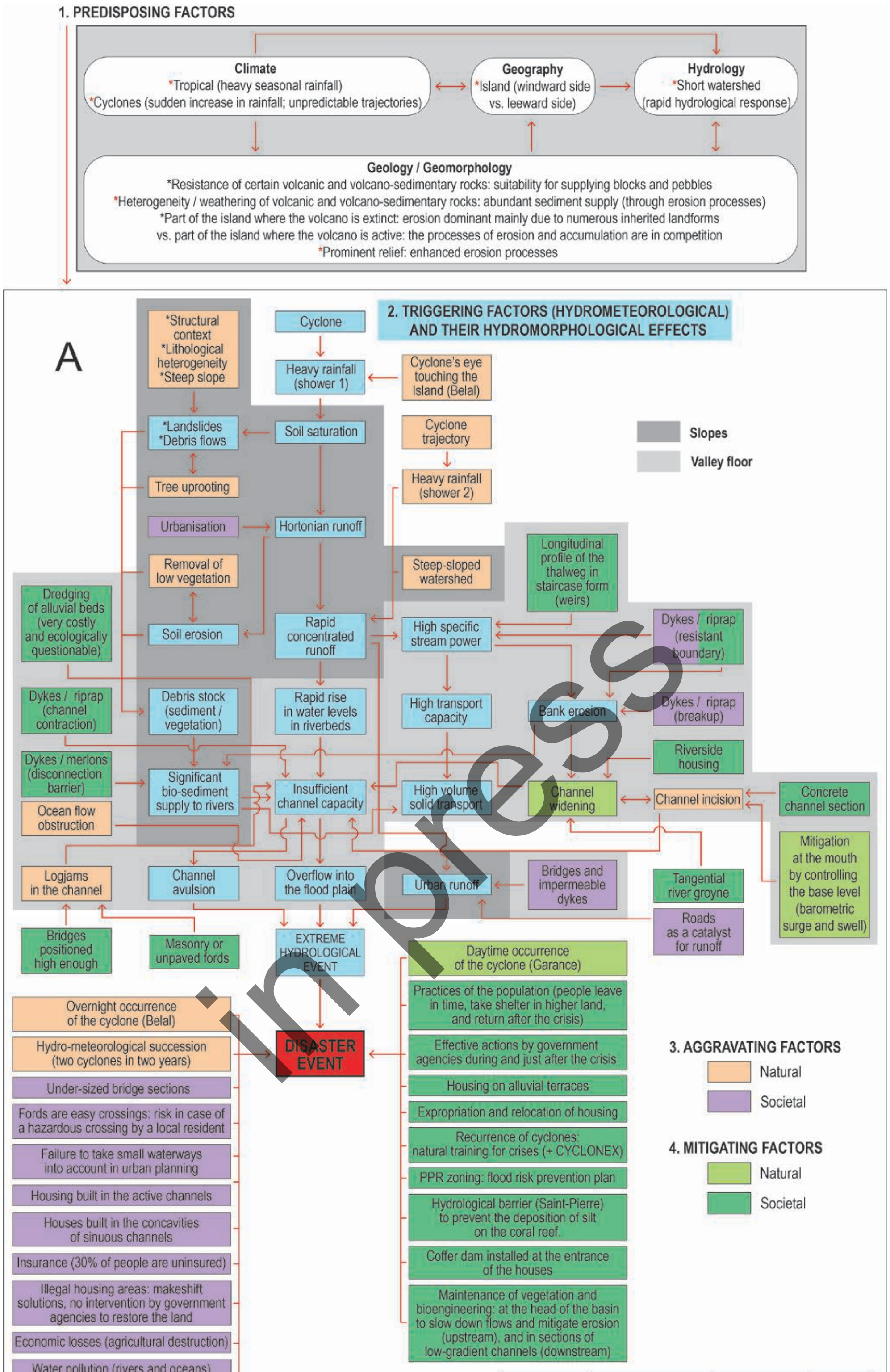
1- système volcanique « Piton des Neiges », 2- système volcanique « Piton de la Fournaise », 3- escarpement de faille, 4- courbe de niveau (en m N.G.F.), 5- point coté (en m N.G.F.), 6- cône central et cratère actif, 7- cratère ancien, 8- maar, 9- rempart de caldeira et cirque circulaires, 10- rempart de caldeira (+ glissement de flanc) semi-circulaire, 11- rempart et cirque en voie de dégagement, 12- crête intercalaire, 13- îlet et colline intra-caldeiras, 14- glissement de terrain majeur, 15- planèze ancienne, 16- planèze récente, 17- haute plaine (forme d'érosion à la jointure entre les deux édifices volcaniques), 18- cours d'eau de flanc (fleuve majeur = « rivière »), 19- cours d'eau de flanc (fleuve secondaire), 20- cours d'eau adjacent (fleuve majeur = « rivière »), 21- cours d'eau adjacent (fleuve secondaire), 22- lac, 23- gorge de raccordement, 24- gorge indifférenciée, 25- cône-delta ancien, 26- cône-delta récent, 27- plaine d'accumulation fluvio-marine indifférenciée, 28- bande active de tressage (avant endiguement des cours d'eau), 29- falaise vive, 30- falaise morte (alignée sur un escarpement de faille), 31- côte basse indifférenciée, 32- cordon littoral à galets (exposé aux fortes houles), 33- plage « relativement » protégée des fortes houles, 34- plage remaniée en dunes éoliennes, 35- récif corallien.

of the ancient Piton des Neiges crater, combined with particularly intense erosion processes such as landslides and torrential events (Salvany et al., 2012). Réunion Island exhibits some of the highest erosion rates in the world, estimated at between 7.2 and 10 mm per year (Gayer et al., 2019). The removal of eroded material from the cirques is facilitated by powerful rivers that have carved deep connecting gorges, ranging from 700 to 1600 m in height, with average slopes exceeding 50°. Through these gorges, extraordinary volumes of sediment are transported, forming delta cones upon reaching the coastline. On the 'planèzes' (*i.e.*, volcanic plateaus that generally slope between 4% and 26 % towards the ocean), the river network is relatively less incised and exhibit a radial pattern. However, some rivers deviate from this pattern, particularly those located at the junction between the two volcanic massifs.

Réunion Island has a subtropical climate characterised by two alternating seasons: a hot and humid southern summer and a dry and cool southern winter. Straddling the 21st parallel, Réunion Island is influenced not only by trade winds originating from the east-southeast (the windward coast) associated with the Mascarene High, but also by the passage of tropical depressions and devastating cyclones (fig. 6C). This, combined with a 3000-m-high orographic barrier, results in a pronounced asymmetry in rainfall distribution – less than 400 mm per year on the western side, compared to between 8000 and 12,000 mm per year on the eastern side – creating over 200 microclimates across the island. Moreover, at any given location, rain may be absent for several months only to fall in abundance over a short period following the arrival of a low-pressure system or a tropical cyclone (such as cyclones Belal and Garance, whose trajectories are depicted in fig. 2B). As a result, Réunion Island holds world records for intense rainfall, including 1825 mm in 24 hours during Cyclone Denise in 1966, 5678 mm in 10 days, and 6083 mm in 15 days during Cyclone Hyacinthe in 1980 (Jumaux et al., 2011).

With a population of 889,679 (2023) spread across 24 municipalities, Réunion Island – currently the most populous French overseas region – is drained by 750 watercourses, of which only about 20 exhibit year-round flow. Locally, watercourses are referred to as 'rivière', equivalent to 'fleuve' in French (Arnaud-Fassetta, 2022), typically when the flow is perennial. Conversely, 'ravine' is used for those which have a temporary flow and can also be referred to as 'fleuve'. However, this classification is not uniformly applied across the island, as some 'ravines' may in fact possess a permanent flow. For the purposes of this paper, the terms 'rivière' and 'ravine' will be used interchangeably with 'river'. Réunion Island has been defined as a "river basin district" (in accordance with the French Water Act derived from the WFD – Water Framework Directive), comprising numerous small, unitary watersheds averaging around thirty square kilometres (with the largest covering 213 km^2). These watersheds feature steep slopes (headwaters: 30 %; thalweg: 12 %), which trigger intense runoff immediately following rainfall, resulting in a torrential flow regime all the way to the sea. The energy of the rivers during floods is immense; for instance, the specific stream power of the Ravine Patates à Durand in Saint-Denis, measured in its channelized section on the delta-cone during Cyclone Hyacinthe in 1980, was estimated at 8240 W/m^2, with a discharge of 240 m^3/s, a gradient of 4 %, an average channel width of 16 m, and a water density (with suspended matter) of 1400 kg/m^3. The channel pattern of large rivers is generally braided in floodplains but meandering with a single channel in narrower areas (*e.g.*, connecting gorges). The predominant bedload is gravelly, with the coarsest materials consisting of boulders and cobbles. For example, grain-size analysis of the bedload of the Rivière des Pluies in Saint-Denis indicates D_{50} and D_{90} values ranging from 3.7 to 8.5 cm and 15 to 40 cm, respectively, over the period from 1966 to 2021 (Roux, 2021). The varying degree of incision of river channels has resulted in the formation of alluvial terraces along their margins, which are, by definition, not subject to flooding as they are inherited landforms (Arnaud-Fassetta, 2008). Aggregate extraction operations within the active channel (*e.g.*, over 1.3 million m^3 extracted from the Rivière des Pluies between 1979 and 1995; Roux, 2021) may have exacerbated the process of channel incision. On the 'planèzes', the hydrographic network, being less mature and therefore less incised, displays greater lateral mobility, particularly due to steeper slopes, with watercourses often adopting a sinuous or straight, single-channel form. Despite the good infiltration capacity of the subsoil (especially in the more recent rocks of Piton de la Fournaise; Join et al., 1997), concentration times remain very short, typically a maximum of around 5 hours for the largest watersheds. These characteristics, combined with very heavy rainfall, can lead to rapid and violent floods (*e.g.*, Rivière du Mât: 2600 m^3/s during Cyclone Hyacinthe in 1980; Bocquée and Givone, 1980). The specific discharges during these floods can reach extreme values, whether measured (*e.g.*, Rivière des Roches: 35.4 m^3.s^{-1}.km^{-2} in 1993 during Cyclone Colina; > 45 m^3.s^{-1}.km^{-2} in small basins heavily impervious due to urbanisation; Observatoire réunionnais de l'eau, 1993) or estimated (*e.g.*, Bras de Cilaos: 52.6 m^3.s^{-1}.km^{-2}; Chetoui, 2019). These specific discharge values rank among the world records (Gaume et al., 2016; Martin-Vide et al., 2019).

Therefore, the disaster risk posed by these flood events becomes evident and measures must be implemented to mitigate their effects, and the impact they will have on the local communities living along the riverside (Dupont et al., 2026; Léone, 2026). Currently, six areas on Réunion Island have been identified as TRI – High-risk flood zones. The conceptualisation of flood risk on Réunion Island, based on the prioritisation of various predisposing, triggering, and aggravating factors, provides a valuable framework for understanding how to address the complex phenomenon resulting from the interactions between natural and societal factors (fig. 3). Unfortunately, the solution adopted for risk management during the 1960s, 1970s, and 1980s entailed the construction of embankments along 'ravines' (Lorion, 1995, 1999, 2006, 2013). Following the commissioning of hydraulic modelling studies in the late 1960s (Perdreau, 1969) and the floods of the 1980s (Duvoisin, 1994), the French government opted to implement a PPER – Multi-year 'ravine' containment programme, and the tenth State-Region Plan further extended the PPER's scope to encompass all watercourses. This containment of 'ravines' has promoted urbanisation and fostered extreme vulnerability behind the dykes. The false sense of security afforded by these dykes has consequently created a new and significant flood risk. The extent of the problem is illustrated by the example of the Ravine Patates à Durand in Saint-Denis (fig. 4). The active channel of the 'ravine' on the cone-delta covered 807,994 m^2 in 1950; today, it spans only



	PREPARATION PHASE (State prevention, training, and education of the population)	SCIENTIFIC KNOWLEDGE AND ACQUISITION OF INFORMATION: Before the event	During the event	Feedback (after the event)	DISSEMINATION OF INFORMATION (State, population, media) on the situation analysis + alert	FIELD ACTIONS DURING THE CRISIS (State, population)
1. Predisposing factors	X	X		X		
2. Triggering factors	X		x	X	X	X
3. Aggravating factors	x		?	X	x	X
4. Mitigating factors	x		?	X	x	X

Fig. 3 – Systemic analysis of flood risk in Réunion Island.

Fig. 3 – Analyse systémique du risque inondation à La Réunion.

75,593 m², representing just 9.6 % of its 1950 footprint. This 90.4 % reduction in the active channel is linked to the channelisation work carried out on the 'ravine' between 1976 and 1987. The successive channelling of the 'ravines' has been perceived as a persistent refusal by the government to acknowledge past floods, thereby removing a potential constraint on urban expansion. The agency currently responsible for managing the DPF – Public, river domain on Réunion Island is the DEAL, whose maintenance involves ensuring the free flow of water. The DEAL must contend with significant structural and functional deficiencies within the river network.

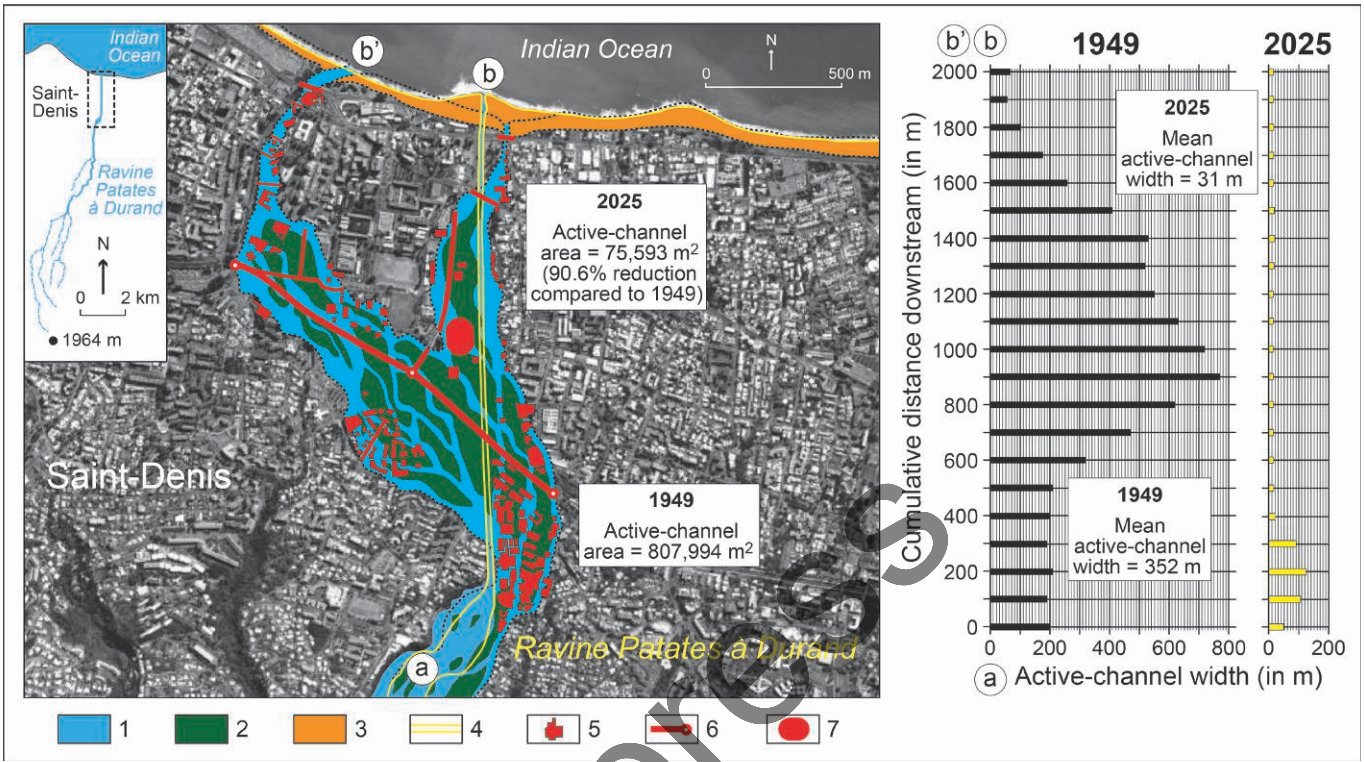


Fig. 4 – The magnitude of the flood-risk problem in Réunion Island, exemplified by the case of Ravine Patates à Durand in Saint-Denis. Between 1976 and 1987, the channel was dammed, leading to a reduction of over 90 % in the active-channel area. Much of the area that made up the active channel in 1949 has since been urbanized.

1- 1949 channels, 2- 1949 alluvial bars, 3- 1949 coastline (gravel beach), 4- 2025 boundaries of the active channel and shoreline, 5- housing within the boundaries of the 1949 active channel, 6- road and roundabout within the boundaries of the 1949 active channel, 7- stadium within the boundaries of the 1949 active channel.

Fig. 4 – L'envergure du problème du risque inondation à La Réunion, illustrée par le cas de la Ravine Patates à Durand à Saint-Denis. *L'endiguement du chenal au cours des années 1976-1987 a conduit à la réduction de la surface de la bande active de tressage de plus de 90 %. Une bonne partie de l'emprise de la bande active de 1949 est aujourd'hui urbanisée.*

1- chenaux 1949, 2- bancs alluviaux 1949, 3- trait de côte (plage graveleuse) 1949, 4- délimitation de la bande active et du trait de côte 2025, 5- habitat dans l'emprise de la bande active de tressage de 1949, 6- route et rond-point dans l'emprise de la bande active de tressage de 1949, 7- stade dans l'emprise de la bande active de tressage de 1949.

3. Methods

This study proposes, through a multidisciplinary approach, to integrate multi-criteria data to analyse river dynamics in the short and medium term and their relationship with land use. The data employed in this paper were primarily acquired as part of the Sar-Dyn programme (2024-2025) of the LABEX DYNAMITE, titled "Réunion's waters in the face of climate change: between societal perceptions and scientific (un)certainties. The ongoing adaptation of an island revealed through fieldwork, research film, and photographic documentary" (Arnaud-Fassetta, 2025a). The principal results of this research were presented to the DEAL Réunion Technical Risk Committee on 9 December 2025 (Arnaud-Fassetta, 2025b), and further highlighted during a photography exhibition in Saint-Denis, Réunion Island (Larive and Arnaud-Fassetta, 2025) and an international conference in Vienna, Austria (Arnaud-Fassetta et al., 2025).

3.1. Data collection

3.1.1. Data from the existing literature

A review of the existing literature enabled the compilation of a significant portion of previous studies and research to assess the current state of knowledge regarding river dynamics in Réunion Island, their impacts, and active-channel management projects. A total of 279 documents were integrated, the majority of which were unpublished reports resulting from commissioned expert assessments conducted by public or private entities on behalf of government agencies. Collaboration with local historians in Saint-Denis facilitated access to unpublished works on river management and the chronology of hydrometeorological hazards. In addition to references specific to the Réunion Island, 73 international references were consulted for the completion of this study. In total, 86 references are cited in the paper's bibliography.

3.1.2. Data from Google and IGN

The usage of Google Earth (https://earth.google.com) and the IGN – French National Geographic Institute (*https://remonterletemps.ign.fr/*) facilitated a diachronic analysis of aerial photographs from 1949 to 2025 to observe morphological changes in riverbeds within their watersheds. The dates of the images selected for analysis (1949-1950, 1961, 1966, 1969, 1978, 1984, 1989, 2000, 2006, 2012, 2023, 2024, 2025) were chosen not only based on image quality but also to closely frame storm periods in order to fully understand the impact of hydrometeorological hazards, and to avoid the cumbersome task of analysing images when no significant activity is occurring along the riverbanks.

3.1.3. Historical data

Online access to the Departmental Archives of Réunion in Saint-Denis provided us with historical documents that enabled us to trace past hydrometeorological events, their impacts on rivers, and the proposed measures to mitigate crises and promote urban development. In particular, we had access to vintage postcards, dated between 1879 and 1930, from which we selected those pertinent to the study of river dynamics, amounting to a total of 120 postcards. This collection of photographs was supplemented by engravings dating from 1833. Additionally, we had access to historical maps of Réunion Island, on which we conducted a survey of the geography of human settlements based on geomorphological units. The dates selected for the analysis of the historical maps (1653, 1700, 1710, 1774, 1848, 1852, 1906, 1950, 2023) were chosen based on the quality of the documents.

3.1.4. Field data

Three scientific expeditions were conducted in 2024-2025: (*i*) from 22 February to 5 March 2024, shortly after Cyclone Belal (15 January 2024); (*ii*) from 16 to 26 June 2024; and (*iii*) from 12 to 25 March 2025, immediately following Cyclone Garance (28 February 2025). In total, this comprised 31 days in the field conducting direct observations, mapping, and stratigraphic surveys. These mission days were also utilised to meet and engage with local stakeholders.

3.2. The data collected and their analysis in relation to the scientific question

3.2.1. Dynamics of hydrometeorological hazards

We were able to define hydrometeorological hazards over several timescales:

- for the "long term" (1863-2025; Rivière de la Grande Chaloupe), we used aerial photographs (1950-2025) to delineate the active channel at the time the photograph was taken. The active channel corresponds to the sum of the width of the water-filled channels and the unvegetated banks (Osterkamp and Hedman, 1982; Rundle, 1985). To quantify the dynamics of the active channel, the satellite photographs were first georeferenced. The WGS 84 – EPSG 3857 projection, corresponding to the coordinate system employed by the map tiles covering Réunion Island, was chosen to ensure spatial consistency and enable metric measurements. Once georeferenced, these images served as a basis for manually digitising the boundaries of the active channel as polylines. A set of 13 aerial photographs (1950, 1961, 1966, 1969, 1978, 1984, 1989, 2000, 2006, 2012, 2023, 2024, 2025) was analysed. Four adjustment variables were calculated: first, (*i*) the active-channel area (A_c; in m^2), obtained by subtracting the area of forested islands from the envelope curve of the active channel; then, based on cross-sections taken every 10 m (*i.e.*, 30 measurements along the studied section), (*ii*) the average active-channel width (W; in m^2), (*iii*) the braiding index (B_I), equivalent to the number of channels minus one (Howard et al., 1970), and the minimum distance between the active channel and the Lazaret buildings (L_{min}). The cumulative margin of error for all these calculations is estimated to be less than 5 % (this margin of error was verified by comparing 30 sections measured directly in the field and on the computer). The analysis of the evolution of these adjustment variables allowed us to identify phases of widening, narrowing, and lateral migration of the active channel. In specific cases, we calculated the sinuosity index (S_I) of the river channels using the equation (Richards, 1982): S_I = channel length (in m) / channel length as the crow flies (in m), with values classified as follows: (quasi)straight channel [1-1.05[; sinuous channel [1.05-1.25[; very sinuous channel [1.25-1.5[; meandering channel [1.5-+∞[. We also employed stratigraphic analysis in the field to identify former active channels, which we dated relatively by comparing their positions in aerial photographs and using the dates of the buildings that overlay them. Continuing our focus on the long term (1879-2025), we compared ground-level photographs of the same location taken between 1879 and 1930 and those taken in 2024-2025 to assess the evolution of the river and the developments constructed around it (Rivière Saint-Denis);

- for the "medium term" (1949-2025), we utilised aerial photographs (1950-2025) to delineate the active channel as it appeared at the time the photograph was taken and to calculate the riverbed adjustment variables using the same criteria as those specified in the previous section. The study was conducted on four watercourses: Ravine Patates à Durand, Saint-Denis; Rivière Saint-Denis, Saint-Denis/La Colline; Grande Ravine des Lataniers, La Possession; and Ravine de la Veuve, Saint-Leu/Le Plate);

- for the "short term" (2024-2025), we were able to assess the impact of Cyclones Belal and Garance on stormwater runoff and river dynamics; in this paper, we focus specifically on the situation in Le Tremblet (Saint-Philippe) and Saint-Denis (Ravine du Butor; Rivière des Pluies), although observations were also made on other rivers (Rivière du Mât; Rivière des Marsouins; Rivière des Remparts; Ravine des Cabris; Rivière d'Abord; Rivière Saint-Étienne; Ravine des Colimaçons; Grande Ravine; Ravine Saint-Gilles; Rivière des Galets). A detailed geomorphological analysis of the valley floor (topography, hydraulics, stratigraphy, comparative imagery) has enabled us to distinguish between the active zone and the alluvial terrace (fig. 5). This distinction is fundamental for assessing flood risk in the valley floors of Réunion Island, since the active channel, which is part of the floodplain (currently active), is prone to flooding, whereas the alluvial terrace (an inherited landform) is no longer flood-prone under the current hydro-geomorphological conditions (Arnaud-Fassetta, 2008). If the alluvial terrace is "reactivated," it once again becomes part of the active channel. The reports consulted on the impacts of Cyclone Garance are not very clear on the distinction between alluvial terraces and the active channel. It is, however, essential to be rigorous and to use the correct terminology to describe two distinct meso-landforms based on their susceptibility to flooding, especially from the perspective of flood-risk analysis and mapping. Furthermore, it was necessary to estimate three hydraulic parameters locally: (*i*) specific stream power (ω, in W/m^2; Bagnold, 1966), on which the active channel's capacity for morphological adjustment depends, is equal to the product of the density of water loaded with suspended matter (γ_w = 1400 kg/m^3), the acceleration due to gravity (g = 9.81 m/s^2), the discharge (Q; in m^3/s), and the water level gradient (s; in m/m), relative to the channel width (W; in m); (*ii*) the bed shear stress (τ, in N/m^2; Du Boys, 1879) of the flow is equal to $\gamma_w.g.s.R$ (R = hydraulic radius); the Shields parameter (τ*, dimensionless; Shields, 1936), which allows determining that the bed load or bank-foot alluvium can be eroded when the value of 0.047 is exceeded, is equal to $\tau/((\gamma_s-\gamma_w).$ D), where γ_s = grain density (25,996.5 N/m^3), γ_w = 9.81 × 1400 = 13,734 N/m^3, and D = grain diameter (in m).

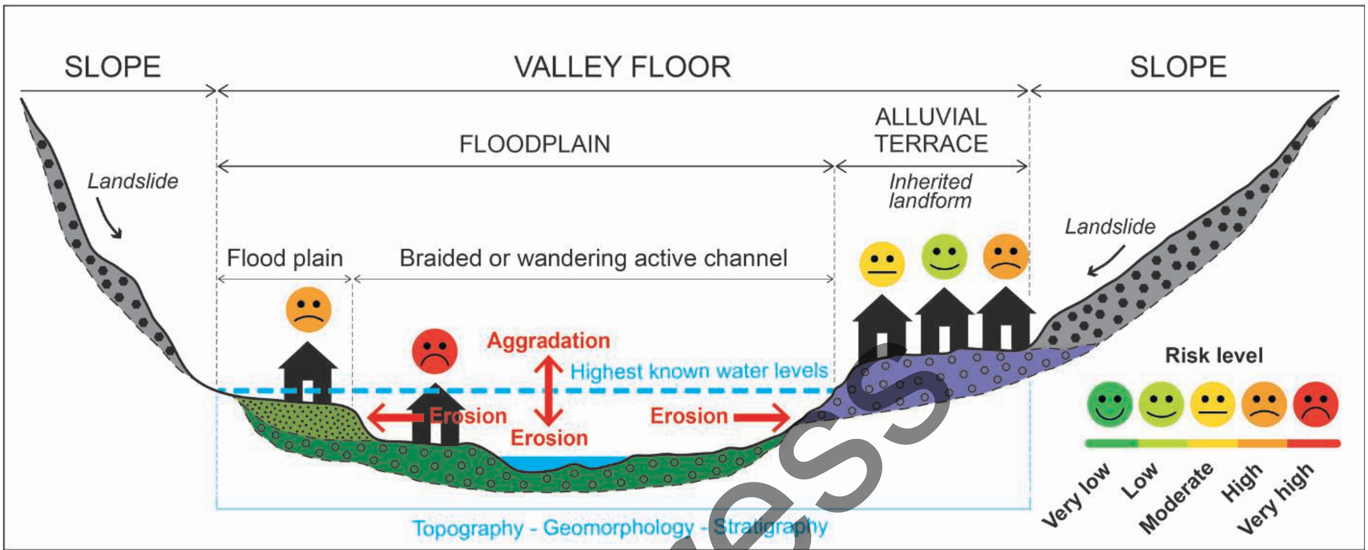


Fig. 5 – Relationships between active and inherited landforms forming the valley floor and flood risk in Réunion Island.

Fig. 5 – Relations entre les formes actives et héritées constituant le fond de vallée et le risque inondation à La Réunion.

3.2.2. Dynamics of housing, population, and structures

Habitat, population, and structural dynamics were examined across several timescales:

- for the "long term", we examined a collection of historical maps spanning from 1653 to 2025. Although maps from the 17th and 18th centuries were analysed, they were deemed unsuitable for quantifying settlements due to their lack of precision and comprehensiveness. For a more precise quantification, we focused on maps from 1820, 1852, 1906, 1950, and 2023, and quantified the number of buildings based on four geomorphological units: 'planèzes', slopes, floodplains, and coastal plains (fig. 6A). In this study, cirques are treated as slopes and floodplains, which does not highlight the complex – and sometimes tragic – history of settlement in these cirques (Fuma, 2004; Bourquin, 2005; Pignon and Rebeyrotte, 2020; Combeau, 2022). Over the period 1820-2023, 463,300 buildings were identified. These data were processed using QGIS software, which allowed us to visualise and analyse the spatial distribution of these settlements and to correlate it with at-risk areas where settlement development continues (Amri, 2025). We compared the number of habitats with the known population of the island during the same period to establish the distribution of the population by geomorphological unit. The results obtained should be interpreted with great caution, given the uncertainties associated with the use of old maps (Germanaz, 2011, 2016). Furthermore, a comparison of engravings (1833) and ground-level photographs of the same location taken between 1879-1930 and 2024-2025 allowed us to track urban growth alongside the development of hydraulic structures along and within riverbeds;
- for the "medium term", a diachronic analysis of aerial photographs (1949-2025) has made it possible to map changes in vulnerability (structural, functional, human) along riverbanks (Ravine Patates à Durand, Saint-Denis; Rivière Saint-Denis, Saint-Denis/La Colline; Ravine de la Grande Chaloupe, Saint-Denis; Grande Ravine des Lataniers, La Possession; Ravine de la Veuve, Saint-Leu/Le Plate);
- for the "short term" (2024-2025), field surveys of local residents enabled us to compare the scientific reality of hydrometeorological hazards (*i.e.*, floods linked to cyclones Belal and Garance) with residents' perceptions and acceptance of these events, particularly in Saint-Denis in the Colline neighbourhood along the Rivière Saint-Denis. We shared this information with scientists and managers. This dialogue with local stakeholders provided us with valuable qualitative insights.

4. Results

4.1. The identification of historical settlements across four types of geomorphological units

The Réunion Island has been at significant risk of flooding since the onset of its colonisation in 1638-1646 (Garnier, 2014). The population has grown from just 12 inhabitants in 1646 to 881,348 in

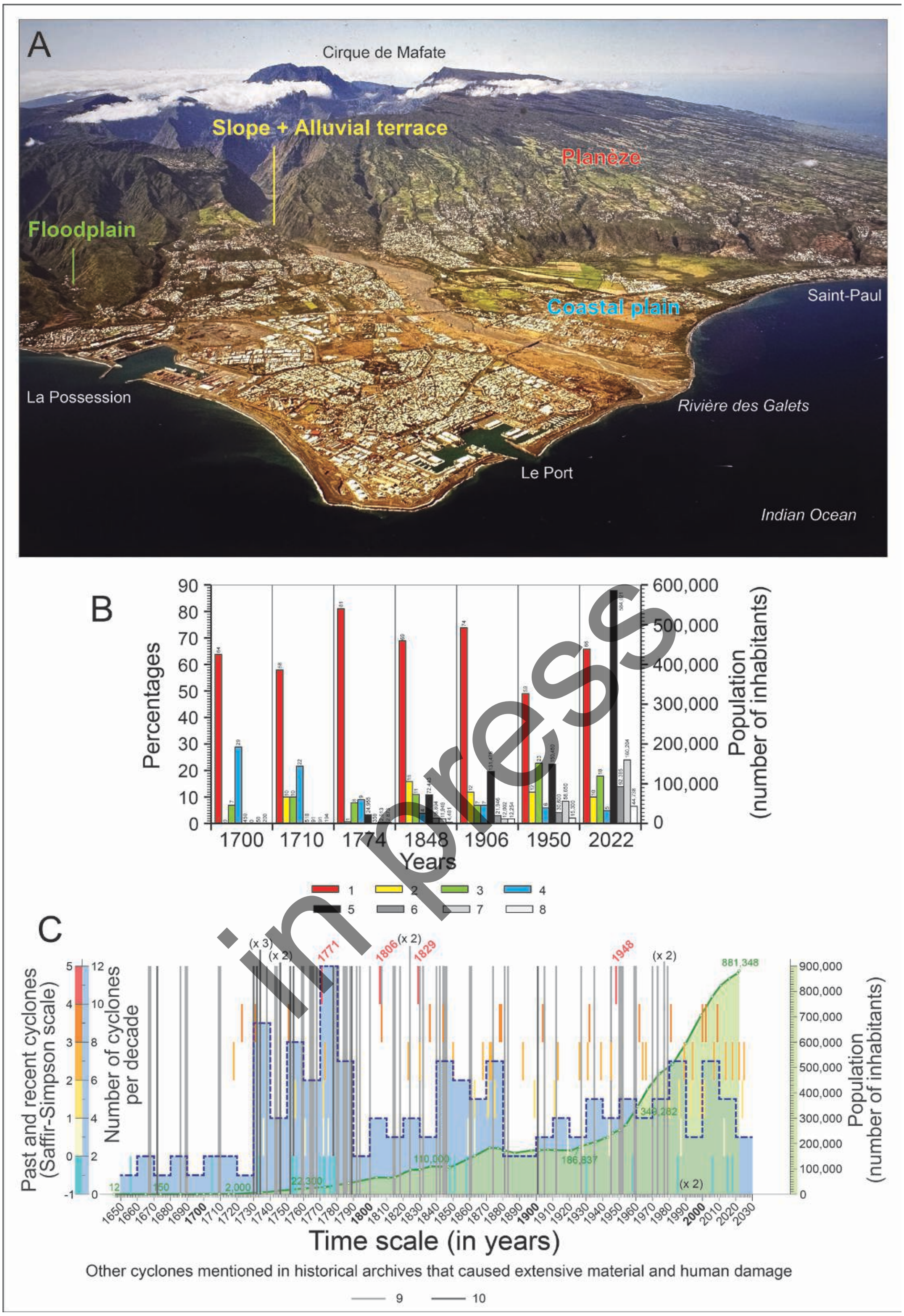


Fig. 6 – Flood risk throughout the history of Réunion Island. A: geomorphological units preferred for settlement (photo: S.C.O.T., 2016). B: changes in the distribution of settlements and population across geomorphological units, based on the analysis of historical and contemporary maps. C: list of cyclones compiled from Garnier (2014), Desarthe and Moncoulon (2017), supplemented by additional historical data.

1- planèze (in %), 2- slopes, including alluvial terraces (in %), 3- floodplain (in %), 4- coastal plain (in %), 5- planèze (in number of inhabitants), 6- slopes, including alluvial terraces (in number of inhabitants), 7- floodplain (in number of inhabitants), 8- coastal plain (in number of inhabitants). 9- notable events, 10- severe events.

***Fig. 6 – Le risque inondation à travers l'histoire de l'île de La Réunion.** A : les unités géomorphologiques privilégiées pour l'implantation de l'habitat (photo : S.C.O.T., 2016). B : évolution de la répartition de l'habitat et de la population sur les unités géomorphologiques, déduite de l'analyse des cartes anciennes et modernes. C : recension des cyclones à partir de la compilation de Garnier (2014), Desarthe et Moncoulon (2017), complétés par d'autres données historiques.*

1- planèze (en %), 2- versants, incluant les terrasses alluviales (en %), 3- plaine alluviale (en %), 4- plaine côtière (en %), 5- planèze (en nombre d'habitants), 6- versants, incluant les terrasses alluviales (en nombre d'habitants), 7- plaine alluviale (en nombre d'habitants), 8- plaine côtière (en nombre d'habitants). 9- événement notable, 10- événement violent.

2022 (fig. 6B). The trajectory of population growth reveals distinct phases: minimal growth during the initial decades of colonisation, a gradual increase during the 'coffee boom', a notable rise between 1820 and 1870, followed by demographic stagnation due to various crises until the 1920s, and an unprecedented population explosion beginning in the mid-20th century. Simultaneously, Réunion Island is frequently affected by cyclones, which contribute to sudden and often catastrophic flooding. Since the 17th century, the island has recorded 162 storms or cyclones that caused damage. The 18th century was the hardest hit, with 53 cyclones, compared to 44 in the 19th century and 43 in the 20th century (fig. 6C).

The severe hydrometeorological conditions on Réunion Island have shaped settlement patterns, compelling populations to adapt to these challenges from the earliest stages of colonisation. Between 1700 and 2022, significant trends emerged in the evolution of the number of settlements and inhabitants (fig. 6B):

- the 'planèzes' have always been the preferred location for settlement, with occupancy rates ranging from 58 % to 81 %. In absolute terms, the population of the 'planèzes' increased considerably, rising from 450 inhabitants in 1700 to 584,021 in 2022;
- slopes, including alluvial terraces, have never accounted for more than 16 % of the island's habitat. However, in absolute terms, the population rose from 91 in 1700 to 92,385 in 2022, with a threefold increase between 1950 and 2022;
- in the valley floors, settlement increased from 7 % to 11 % in the early years to 23 % in 1950 and 18 % today. This growth is even more pronounced in absolute terms, with the population currently reaching 160,204 people, compared to fewer than 59,000 in 1950 and earlier;
- the coastal plains, which differ from the "coastal fringe" of the territorial division, have experienced a steady decline in settlement, falling from 29 % in 1700 to just 5 % in 2022. However, in absolute terms, the population reached a record high, with 44,738 inhabitants in 2022.

Ultimately, the proportion of the population living in the highlands (defined as areas located at an altitude of more than 400 m) rose from 23 % in 1906 to 39 % in 1950, but subsequently declined to 28 % by 2022. On the 'planèzes', the densification of housing, coupled with a significant increase in population, has heightened the risk of urban runoff and flash flooding, particularly in small watercourses. In the municipality of Trois-Bassins, the number of buildings on the 'planèzes' is now two to three times higher in 2024 than it was in 1900-1910 (Arnaud-Fassetta et al., 2025). The growing population in the valley floors has now made this area a significant risk zone.

Historical data indicate that cyclones, although destructive, do not generally result in exceptionally high death tolls (Garnier, 2014). However, there are marked ethnic and social disparities in the mortality rates associated with these natural disasters. The damage caused by cyclones to homes is strongly influenced by construction quality, with a distinction between simple structures ('paillottes') and more durable houses ('cases'; Compain, 2006). More significant than the cyclones themselves are the secondary effects of flooding, which can lead to widespread destruction of crops and infrastructure, economic disruption, food insecurity, and health risks. Crops grown by families have demonstrated greater resilience than more commercially speculative crops, such as coffee and cloves. Ancient societies did not passively endure the adverse effects of the climate; rather, they actively sought to coexist with cyclone-driven waters and mitigate their dangers. At the start of colonisation, residents sought refuge in nearby forests to escape flooding. In the 18th century, rudimentary yet effective warning systems began to be established in ports and churches. Following the cyclones of 1806 and 1807, which caused extensive damage to coffee and spice plantations, these operations were not resumed. Instead, sugarcane, a more resilient crop, was introduced, marking a significant shift in agricultural practices.

4.2. On 'Planèzes' and alluvial fans: The failure to account for the lateral movement of watercourses, the underestimation of "small" rivers, and the neglect of stormwater runoff

4.2.1. Impact of the forced lateral migration of the Ravine de la Veuve

The Ravine de la Veuve originates at Piton Mare in Boue (1227 m) and flows into the Indian Ocean further south, 500 m southeast of Cap Malizé – also known as Église Requins – after a 7.3 km course through a 4.2 km^2 catchment (fig. 7A). In the higher lands of Saint-Leu (Le Plate), the Ravine de la Veuve, which traverses the study area at elevations between 750 and 719 m, cuts 5 to 10 m deep into the Grand Bénare 'planèze' (tuff and volcanic ash from Piton des Neiges). Its unique, sinuous channel (S_i = 1.17) has an average cross-sectional width of 8 m and an average gradient of 10 %. Its specific stream power, estimated at 8240 W/m^2 (with a discharge of 48 m^3/s), and its bed shear stress of 1827 N/m^2 during the flood of 15 January 2024 (Belal), provide it with the capacity to easily remobilise the bedload (D_{50} = 0.3 cm; D_{90} = 50 cm) and the sediments comprising the banks (D_{50} = 0.1 cm; D_{90} = 10 cm), with the Shields parameter reaching 0.298. In 1950, the channel exhibited marked sinuosity (a) upstream of the D3 departmental road bridge, and on the left bank, which was uninhabited at the time, a landslide was observed (fig. 7B). Between 1950 and 2023, the channel continued to migrate toward the concave bank, which has since been developed with several houses. The sinuosity at point a has increased, whereas the sinuosities upstream (b) and downstream (c) have tended to decrease due to channel realignment. Two reasons explain the acceleration of the channel's lateral migration at point a: (*i*) autocyclicity (Beerbower, 1964; Métivier, 2003), a self-adjustment phenomenon that causes a river channel to migrate towards its concave bank due to centrifugal force shifting maximum flow velocities towards that bank, exacerbated by (*ii*) the undersized bridge (fig. 7D), which blocks the meander sequence in the medium term and intensifies erosion on the concave side. This situation led to a landslide caused by undercutting of the riverbank during the flood of 15 January 2024, triggered by the intense rains of Cyclone Belal. Several houses were heavily damaged (fig. 7C).

4.2.2. The under-sizing of the Ravine Montplaisir and the failure to account for stormwater runoff in Saint-Denis

Draining a catchment of 1.2 km^2, the Ravine Montplaisir originates at an elevation of 800 m on the Brulé 'planèze', carved into the weathered rocks of Piton des Neiges (fig. 8A). It flows northward for 4.5 km before joining the Ruisseau des Noirs at an elevation of 20 m.

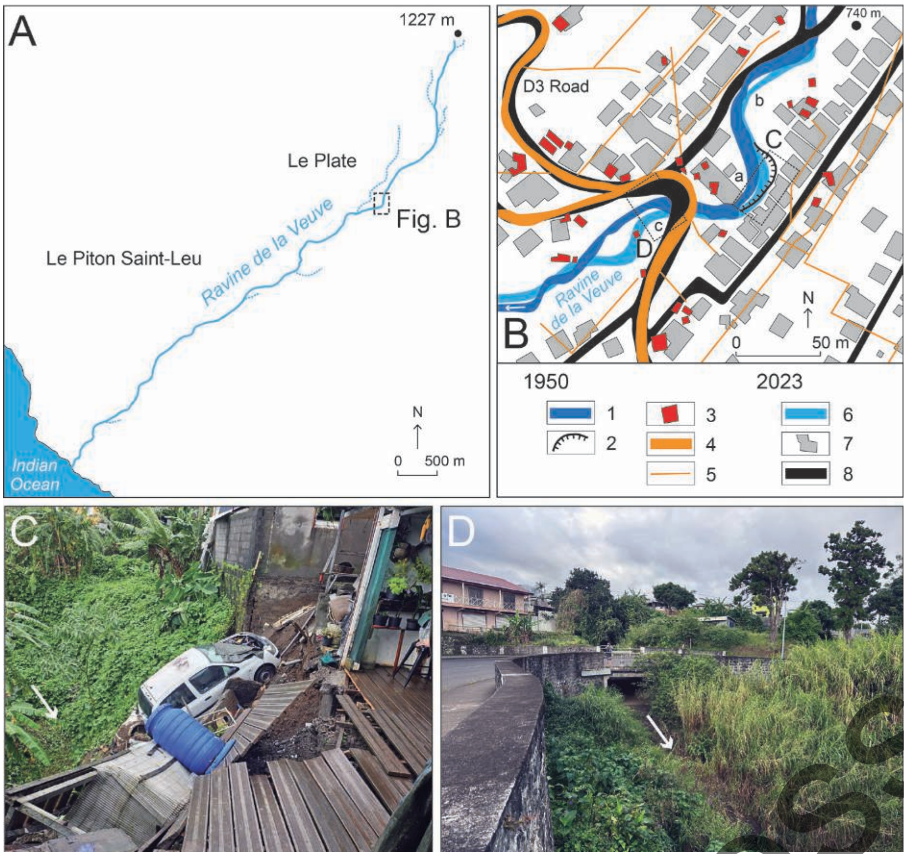


Fig. 7 – Lateral migration of the Ravine de la Veuve on the Saint-Leu planèze (Le Plate). A: location. B: lateral migration towards the concavity of the channel, which remains relatively shallow. C- damage caused by bank erosion on the channel concavity during Cyclone Belal (photo: Mairie de Saint-Leu, January 2024). D- under-sizing of the bridge section downstream of the bank erosion (photo: G. Arnaud-Fassetta, June 21, 2024).

1- channel in 1950, 2- landslide affecting the riverbank in 1950, 3- housing in 1950, 4- roads in 1950, 5- paths in 1950, 6- channel in 2023, 7- housing in 2023, 8- roads in 2023.

Fig. 7 – Migration latérale de la Ravine de la Veuve sur la planèze de Saint-Leu (Le Plate). *A : localisation. B : migration latérale vers la concavité du chenal encore peu encaissé. C- dégâts provoqués par le sapement de berge en rive concave lors du cyclone Belal (photo : Mairie de Saint-Leu, janvier 2024). D- sous-calibrage de la section du pont en aval du sapement de berge (photo : G. Arnaud-Fassetta, 21 juin 2024).*

1- chenal de 1950, 2- glissement de terrain affectant la berge de 1950, 3- habitat de 1950, 4- route de 1950, 5- chemin de 1950, 6- chenal de 2023, 7- habitat de 2023, 8- route de 2023.

The latter ends its course 265 m further downstream in the Ravine du Butor, the catchment's main watercourse, which is then only 1.21 km from the Indian Ocean into which it flows, its mouth being located 2.2 km southeast of Pointe des Jardins (Cap du Barachois). The study area is situated in the Providence neighbourhood, where part of the Ravine Montplaisir had to be channelled in 1984-1985 to allow for the development of a ZAC – Concerted development zone and the construction of a group of apartment buildings (fig. 8B). In the channelled section, the 'ravine' bed measures 2.5 x 2 m, or 5 m^2, whereas 300 m upstream of the development, the bed area – widened by the flood of 28 February 2025 (Cyclone Garance) – measures 12 x 2 m, or 24 m^2. It is easy to conclude that the under-sizing of the 'ravine' as it crosses the ZAC has caused recurring overflows in the densely populated neighbourhood for the past 40 years (Lorion, 2006), which was the case in February 2025 (fig. 8C). In addition to this problem of river flooding, there is also the issue of stormwater runoff. Nothing is being done here to collect rainwater, which rushes violently through the streets, acting as a launch pad for the runoff (fig. 8D).

4.2.3. From under-sizing to the avulsion of young 'ravines' in Saint-Philippe

In the Sud Sauvage region, closely linked to the volcanic activity of the Piton de la Fournaise, a small 'ravine' has formed along the path of the 1986 Citrons Galets lava flow, between the Pointe de la Table to the south and the Pointe du Tremblet to the north (fig. 9A). The Ravine des Citrons Galets, which is 8.6 km long, has an average gradient of 21 % within a very elongated watershed of 2 km^2 that includes the hamlet of Le Tremblet, part of the municipality of Saint-Philippe. Le Tremblet is the last cluster of homes one passes through on National Route 2 in the direction of Saint-Philippe/Saint-Joseph before reaching the Tremblet rampart, located 1 km to the north, which marks the boundary of the Enclos Fouqué, the last caldera formed by the volcano. While the residents of Le Tremblet were evacuated in April 2007 during the eruption of Piton de la Fournaise, they also face the threat of sudden flash floods. The recently formed 'ravine' under study is very shallow (less than 5 m) and its course remains highly uncertain, making it a dangerous river as it is prone to rapidly changing its path during floods. This was precisely the case on 15 January 2024 during the passage of Cyclone Belal. Between 13 and 16 January 2024, between 750 and 1000 mm of rain fell on Piton de la Fournaise. In the study catchment, total rainfall over these four days ranged from 750 mm upstream to 200 mm downstream (MétéoFrance data). These heavy downpours rapidly increased the flow in the Ravine des Citrons Galets, which could have been managed if (1) the 9 m^2 cross-section had not been virtually blocked by a bridge and severely undersized culverts (2 m^2) at the Tremblet crossing (fig. 9B). The rapid flow (5 m/s) over a local slope of 15 % generated a specific power of 30,902 W/m^2 and a bed shear stress of 2060 N/m^2. The deposits of suspended sediment (e) on the wall of the house on the left bank attest to the violence of the flow. The overflow of water from the 'ravine' caused (2) the flooding of the house on the left bank. (3) The low wall along the road, which is perpendicular to the flow, caused additional flooding and diverted the overflowing channel's flow (4) to the right, where it followed a private road through the housing development (fig. 9D) and flooded several houses, and (5) to the left, where it rushed down the slope and carved out a channel through scouring (fig. 9C). This new channel is 6 m wide and 1 m deep. Its formation was caused by vigorous flows,

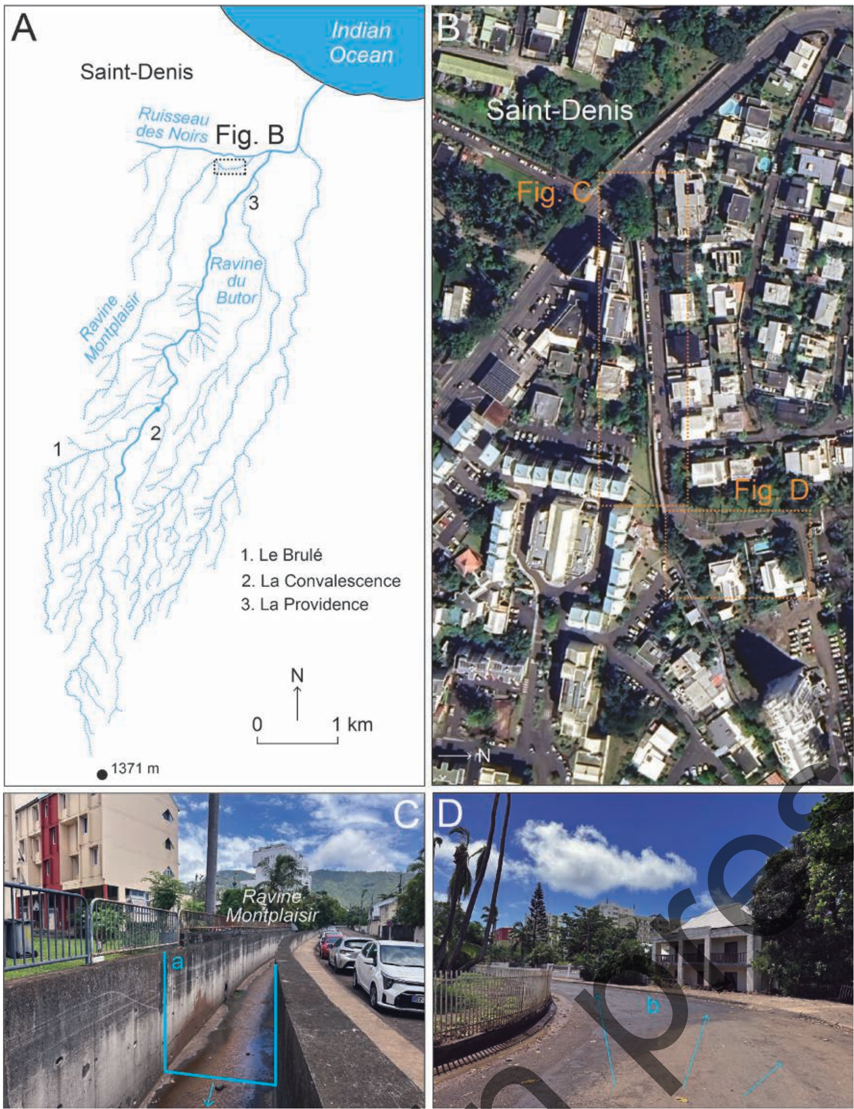


Fig. 8 – Under-calibration of the river sections in urban areas (Ravine Monplaisir, watershed of the Ravine Butor in Saint-Denis). A: location. B: channelized section. C: wet section at bankfull stage (a) less than 5 m², resulting in recurrent overflows in the urban area (photo: G. Arnaud-Fassetta, March 21, 2025). D: overflow area downstream of the channelized section, following Cyclone Garance (photo: G. Arnaud-Fassetta, March 21, 2025). b: overflowing water from the river and rainwater runoff directed by the road along the river.

Fig. 8 – Sous-calibrage des sections de rivière en ville (Ravine Monplaisir, bassin-versant de la Ravine du Butor à Saint-Denis). *A : localisation. B : section chenalisée. C : section mouillée à pleins bords (a) inférieure à 5 m², conduisant à des débordements récurrents dans la zone urbanisée (photo : G. Arnaud-Fassetta, 21 mars 2025). D : zone de débordement en aval de la section chenalisée, après le passage du cyclone Garance (photo : G. Arnaud-Fassetta, 21 mars 2025). b : eaux de débordement de la ravine + écoulements pluviaux guidés par la route le long de la ravine.*

with an estimated specific stream power of 16,481 W/m² and a bed shear stress of 1545 N/m². Under these conditions, the bedload – with a D_{50} of 3 cm and a D_{90} of 50 cm – was largely flushed out during the flood, with the Shields parameter reaching 0.252.

4.3. Dykes intended to "secure" low-lying neighbourhoods in the floodplain have significantly reduced the lateral movement of waterways and do not incorporate stormwater runoff into their design

The construction of dykes along the 'rivières' and 'ravines' of Réunion Island began as early as the 18th and 19th centuries (Hoarau, 2012) to "secure" the floodplain and legitimize the development of new urban areas. This policy of dyke construction reached its peak with the implementation, in 1984, of the PPER – Multi-year 'ravine' containment plan, which was, however, incompatible with the flood risk zoning adopted in 1982 and implemented as early as 1984 by the French government through the PERs – Risk exposure plans, which would later become the PPRs – Risk prevention plans in 1995. The reason for this exemption from the Water Act in Réunion Island is attributed to the desire to develop large-scale real estate projects in areas of the catchments that would inevitably have been classified as red zones (*i.e.*, no-build zones) in the PERs (Lorion, 2006).

In the catchment (31.7 km²) of the Rivière Saint-Denis (length: 15.4 km), the active channel widened sixfold during the 19th century and fivefold during the 20th century, causing severe damage to residential, industrial, and artisanal areas as well as to bridges and dykes (Lorion, 2006). These sudden phases of widening of the active channel, resulting from intense rains brought by cyclones, occurred at least as far back as 1830-1832, when the riverbed was not yet embanked (fig. 10A), but they may also have occurred after the riverbed was embanked. For example, on March 4, 1913, the Rivière Saint-Denis, which had been dammed in the latter half of the 19th century, saw its right-bank dyke breach during a cyclone (fig. 10B). The active channel extends well beyond the dyke's boundaries; the dyke was subsequently rebuilt in the same location without accounting for the river's historical floodplain (fig. 10C). Today, the densely urbanised lower right-bank neighbourhood (known as "Bas de la rivière") lies within the footprint of the 1913 active channel.

The design of dykes very rarely takes urban runoff into account. Indeed, these dykes are impermeable, and their primary function is to contain the flow along the river and prevent potential flooding of residential areas. In fact, the embankment that encloses the river prevents stormwater runoff from reaching the river (fig. 10B and

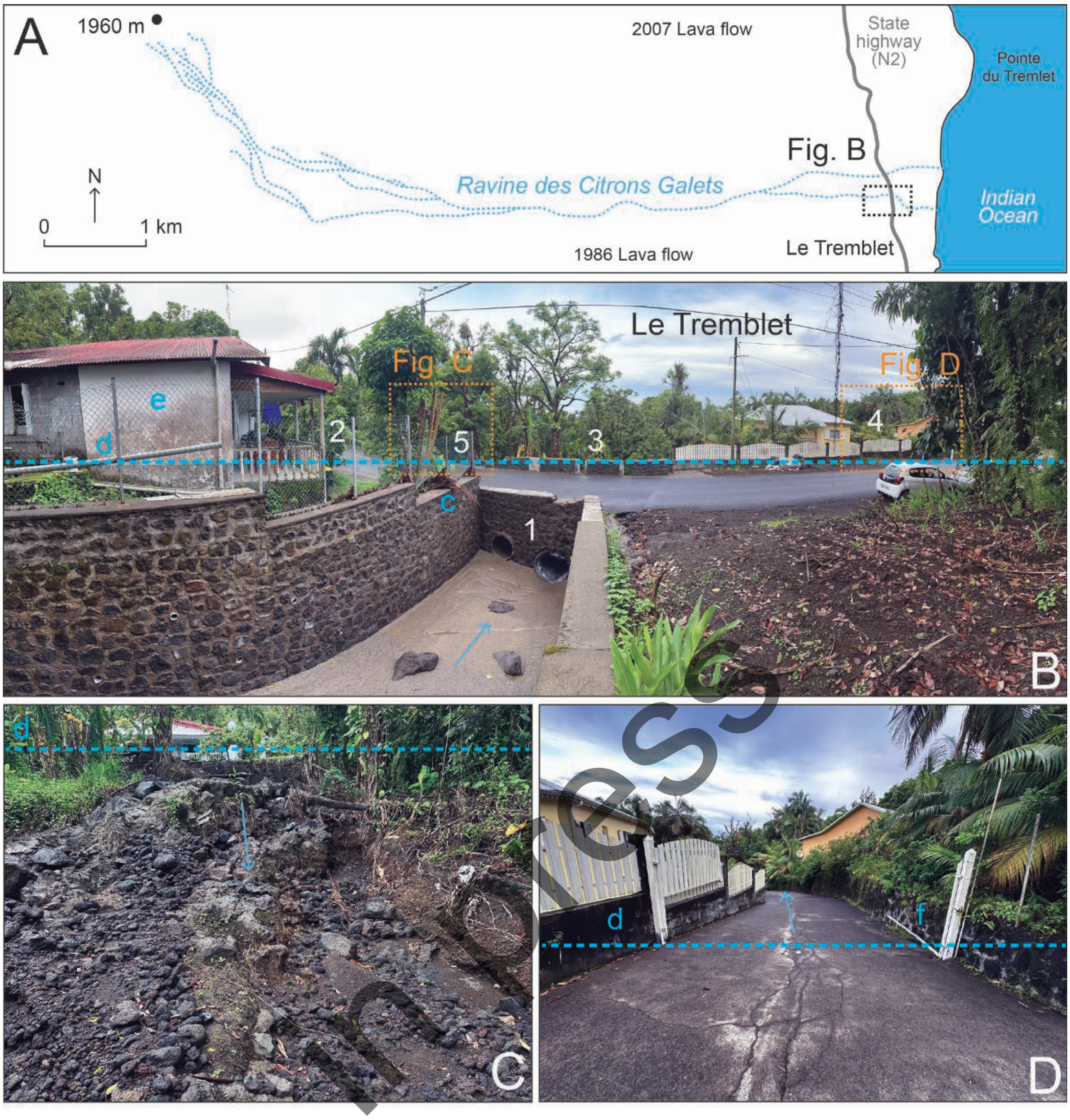


Fig. 9 – Under-calibration of bridges (Ravine des Citrons Galets in Saint-Philippe, Le Tremblet). A: location. B: overflow from the river into the urban area during Cyclone Belal (photo: G. Arnaud-Fassetta, March 4, 2024). C: channel opened in February 2024 due to drainage caused by hydraulic and road works (photo: G. Arnaud-Fassetta, March 4, 2024). D: private road that directed floodwaters into the housing development (photo: G. Arnaud-Fassetta, March 4, 2024).

1- under-calibration of the culvert section under the bridge, 2- overflow from the river and flooding of the house on the left bank, 3- low wall along the road causing overflooding and redirecting the flow of the overflowing channel, 4- to the right, the flow follows the private road through the housing development (D), flooding several houses, 5- to the left, the flow rushes down the slope and opens a channel through avulsion process (C), c = flood mark, d = water level, e = water and suspended matters splashed onto the wall of the house, f = entrance gate to the housing development destroyed by floodwaters.

Fig. 9 – Sous-calibrage des ponts (Ravine des Citrons Galets à Saint-Philippe, Le Tremblet). A : localisation. B : débordement de la ravine dans la zone urbanisée lors du cyclone Belal (photo : G. Arnaud-Fassetta, 4 mars 2024). C : chenal ouvert en février 2024 par défluviation provoquée par les aménagements hydrauliques et routiers (photo : G. Arnaud-Fassetta, 4 mars 2024). D : chemin privé ayant conduit les eaux de débordement dans le lotissement (photo : G. Arnaud-Fassetta, 4 mars 2024).

1- sous-calibrage de la section busée sous le pont, 2- débordement des eaux de la ravine et inondation de la maison en rive gauche. 3- muret le long de la route qui provoque une sur-inondation et dévie les flux du chenal débordant, 4- vers la droite, les flux suivent le chemin privé traversant le lotissement (fig. D) et inonde plusieurs maisons, 5- vers la gauche, les flux dévalent la pente et ouvrent un chenal par défluviation (fig. C), c = laisse de crue, d = hauteur d'eau, e = projection d'eau et de boue sur le mur de la maison, f = portail d'entrée au lotissement détruit par les eaux de crue.

11C). This structural failure was the cause of storm flooding in the valley floors in 2024-2025. In the Rivière Saint-Denis, stormwater runoff, already blocked by the river dyke, was exacerbated by the lack of control over urban runoff (fig. 11). On the left bank, on the lower terrace sloping at 6 % between 55 and 15 m in elevation, lies the neighbourhood known as "Petite Île". The eastern edge of this lower terrace connects to the valley floor via a slope ranging from 12 m (upstream) to 3 m (downstream) in height. The valley floor consists of the lower alluvial terrace, which has been flood-proofed by the construction of a levee separating it from the floodplain where the active channel of the Rivière Saint-Denis extends. On 28 February 2025, the heavy rain brought by Cyclone Garance caused runoff

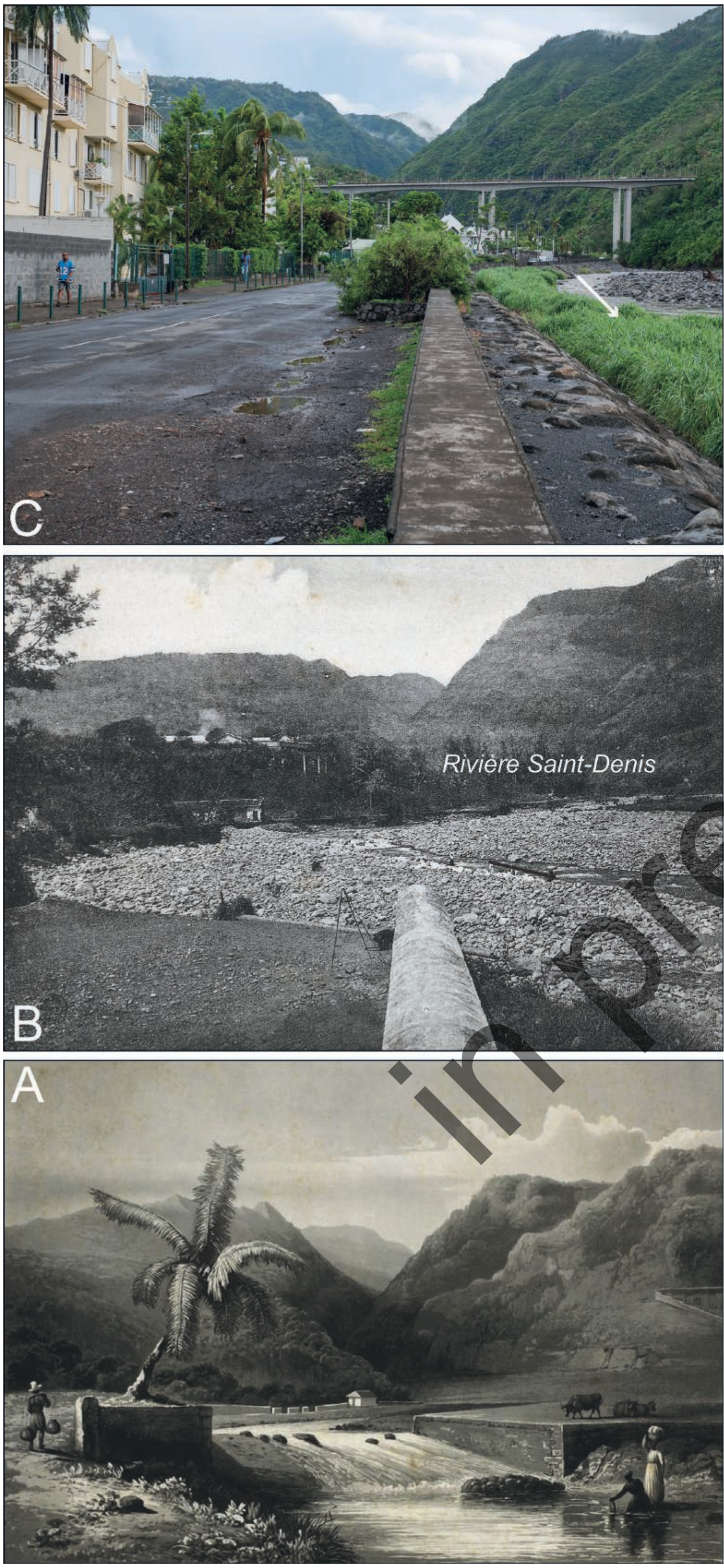


Fig. 10 – Identical reconstruction of dykes (Rivière Saint-Denis, Saint-Denis). A: the Rivière Saint-Denis in 1830-1832 (an 1833 engraving from the historical atlas "Voyage around the world via the Indian and Chinese seas undertaken by the State corvette La Favorite in 1830, 1831, and 1832", published by Cyrille Pierre Théodore Laplace in 1835 on the occasion of a scientific and commercial mission). The river is not dammed, but it is already equipped with a weir built under the direction of Gabriel Amédée Marie Bédier, mayor of Saint-Denis from 1832 to 1848. This weir facilitated access to the river for the servants of Saint-Denis, who came in the afternoon to fetch fresh water for the evening meal. The valley floor is undeveloped: only a single house stands on the edge of the active channel of a wandering, meandering river. B: the Rivière Saint-Denis, dammed in the second half of 19th century, experienced a dyke breach during the cyclone of March 4, 1913. The active channel extends well beyond the limits of the dyke. C: the Rivière Saint-Denis today (photo: J. Larive, March 22, 2025). The dyke has been rebuilt in the same location, without considering the river's historical mobility space, resulting in the lower neighbourhood on the right bank being situated within the active channel of 1913. See location in fig. 11.

Fig. 10 – La reconstruction à l'identique des digues (Rivière Saint-Denis, Saint-Denis). *A : la rivière Saint-Denis en 1830-1832 (gravure de 1833 extraite de l'atlas historique « Voyage autour du monde par les mers de l'Inde et de Chine exécuté par la corvette de l'État La Favorite pendant les années 1830, 1831 et 1832 », publié par Cyrille Pierre Théodore Laplace en 1835 à l'occasion d'une mission scientifique et commerciale). La rivière n'est pas endiguée mais elle est déjà équipée d'un seuil construit sous l'égide de Gabriel Amédée Marie Bédier, maire de Saint-Denis de 1832 à 1848. Ce seuil facilitait l'accès de la rivière aux domestiques de Saint-Denis, qui venaient dans l'après-midi y chercher l'eau fraîche pour le repas du soir. Le fond de vallée n'est pas urbanisé : seule une maison apparaît en marge de la bande active d'une rivière sinueuse et divagante. B : la rivière Saint-Denis, endiguée dans la seconde moitié du XIX*[e] *siècle, voit sa digue se rompre lors du passage du cyclone du 4 mars 1913. L'extension de sa bande active de tressage va bien au-delà des limites de la digue. C : la rivière Saint-Denis aujourd'hui (photo : J. Larive, 22 mars 2025). La digue a été reconstruite au même endroit, sans tenir compte de l'espace de mobilité historique de la rivière, et le bas quartier en rive droite est dans l'emprise de la bande active de tressage de 1913. Localisation sur la fig. 11.*

whose flows were channelled along roadways, most of which were lined with walls. One of these stormwater systems, possibly fed by runoff from a 'ravine' descending from La Vigie, originates in the Caserne Lambert area and flows all the way to the last road bridge spanning the Rivière Saint-Denis in the direction of Saint-Denis (fig. 11A). At the bridge, the section is 10 m wide, and the slope is 3 % between the roundabout and the bridge. The water depth was measured at 40 cm from the flood marks (fig. 11B), which, with a flow velocity of 1 to 2 m/s, yields a discharge of 4 to 8 m^3/s. The flood mark, consisting of floating debris accumulated against the low wall along the road and the railing attached to the bridge deck, may have increased the height of the runoff water on the bridge. Ultimately, much of this runoff water passed

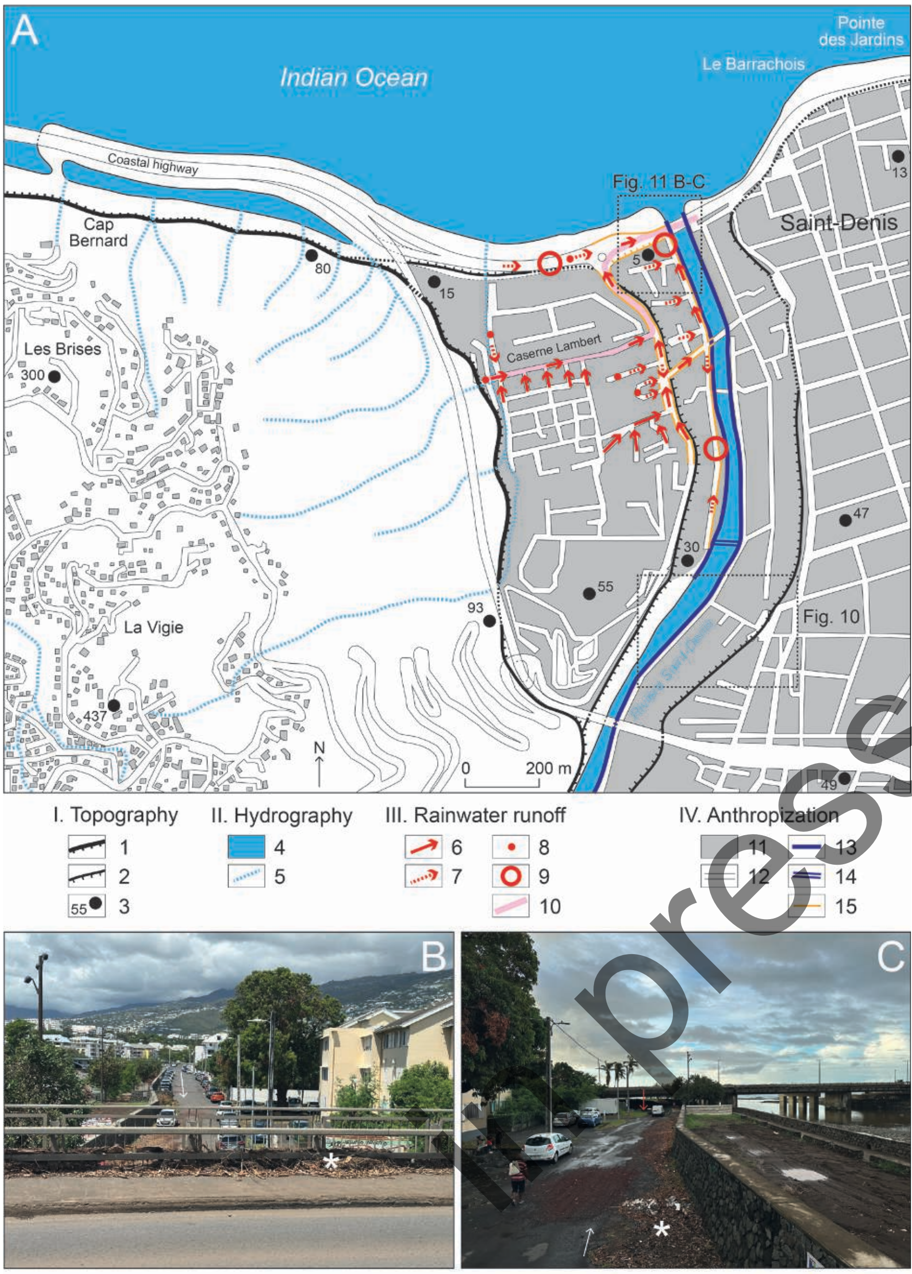


Fig. 11 – Urban runoff causing flooding in the lower part of the Saint-Denis neighbourhood near the mouth of the Rivière de Saint-Denis on the left bank. The flooding, which occurred on February 28, 2025 (Cyclone Garance), was caused by runoff originating in the Caserne Lambert area that flowed through the road network and reached the bridge furthest downstream. It was from this bridge that the water flowed through the railing attached to the bridge deck, flooding the houses located below. A: explanatory sketch. B: flood mark (*) on the low wall along the road and a railing attached to the bridge deck, indicating flows of at least 40 cm in height (photo: G. Arnaud-Fassetta, March 22, 2025). The white arrow indicates where rainwater flows in from the side and from upstream along the dyke. C: the flooded neighbourhood below the bridge (photo: G. Arnaud-Fassetta, March 22, 2025). The white arrow indicates rainwater runoff flowing laterally and from upstream along the river dyke; the red arrow indicates runoff flowing from the bridge. The white asterisk indicates floating debris (flood mark).

1- major slope passing toward the downstream at a cliff, 2- minor slope cutting into old lava flows, 3- elevation point (in m a.s.l.), 4- rivière Saint-Denis (February 28, 2025), 5- temporary flow, 6- major urban runoff, 7- minor urban runoff, 8- runoff source area, 9- runoff destination area, 10- dominant runoff path, 11- residential areas and green spaces, 12- road, 13- dyke, 14- weir, 15- wall.

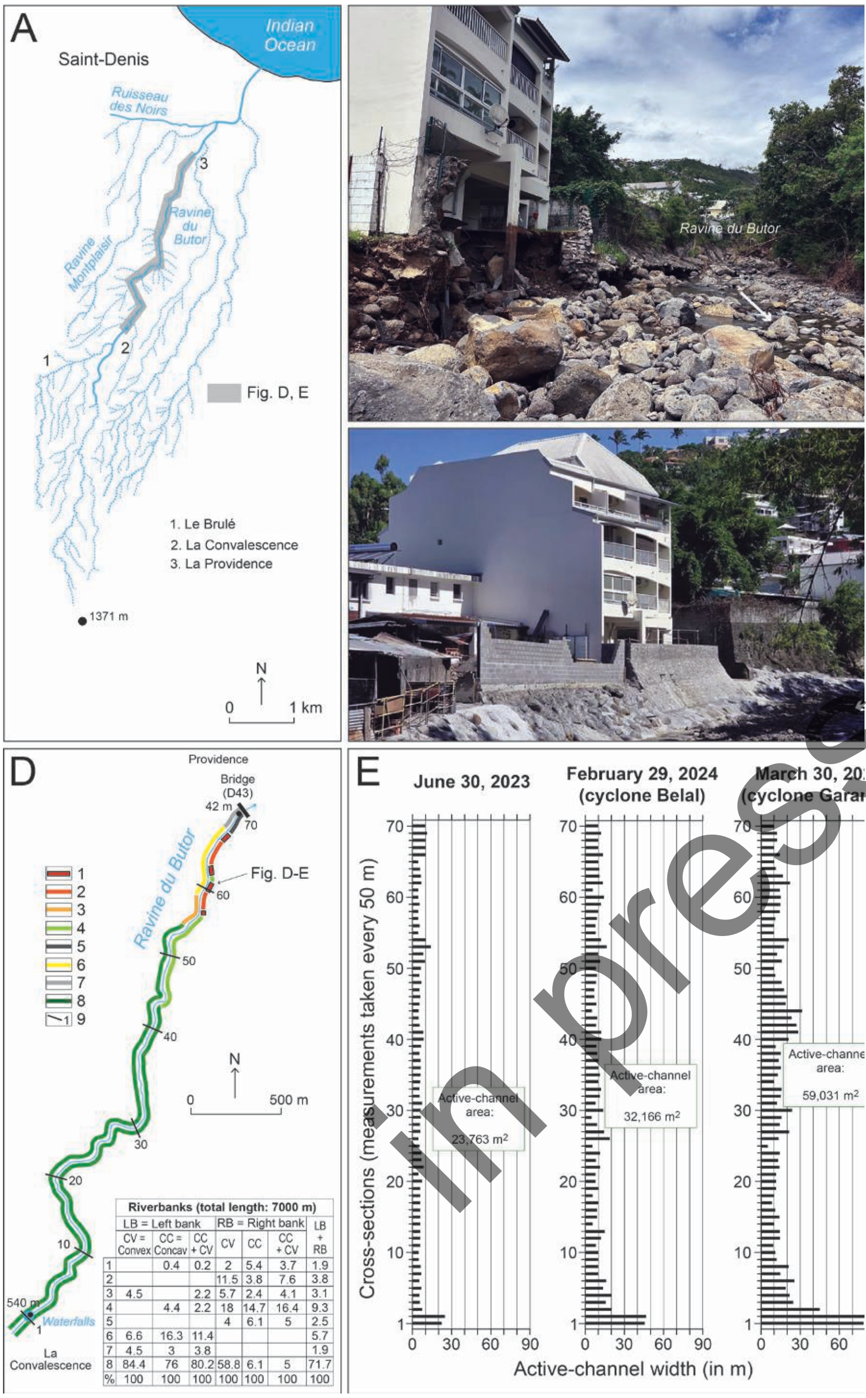
Fig. 11 – Ruissellement urbain à l'origine de l'inondation du bas quartier de Saint-Denis proche de l'embouchure de la Rivière Saint-Denis en rive gauche. *L'inondation, qui s'est produite le 28 février 2025 (cyclone Garance), a été provoquée par des écoulements partis du secteur de la Caserne Lambert et qui ont réussi à atteindre le pont le plus à l'aval via le réseau routier. C'est à partir de ce pont que l'eau a coulé à travers la balustrade fixée au tablier, inondant les maisons situées en contre-bas. A : cartographie. B : laisse de crue (*) sur le muret de la route et la balustrade du pont, indiquant des écoulements d'au moins 40 cm de hauteur (photo : G. Arnaud-Fassetta, 22 mars 2025). La flèche blanche indique l'arrivée du ruissellement pluvial latéralement et depuis l'amont le long de la digue. C : le quartier inondé en contrebas du pont (photo : G. Arnaud-Fassetta, 22 mars 2025). La flèche blanche indique l'arrivée du ruissellement pluvial latéralement et depuis l'amont le long de la digue, la flèche rouge les eaux de ruissellement arrivant du pont. L'astérisque blanche indique les débris flottants (laisse de crue).*

1- versant majeur se prolongeant vers l'aval en falaise, 2- partie basse du versant entaillant d'anciennes coulées de lave, 3- point coté (en m N.G.F.), 4- rivière Saint-Denis (28 février 2025), 5- écoulement temporaire, 6- ruissellement pluvial majeur, 7- ruissellement pluvial mineur, 8- zone de départ de l'écoulement, 9- zone d'arrivée de l'écoulement, 10- trajectoire préférentielle du ruissellement, 11- habitat et espaces verts, 12- route, 13- digue, 14- seuil, 15- mur.

through the railing, flooding the houses located below the bridge (fig. 11C). The dyke also channeled runoff arriving from the sides and from upstream. Ultimately, this is how an alluvial terrace, normally protected from flooding, can be inundated by stormwater runoff.

4.4. Identical reconstruction along the riverbanks: an absolute necessity?

Extensive damage occurred locally in the catchments affected by the heavy rains from cyclones Belal and Garance, necessitating emergency measures to repair and protect homes and their occupants. This was the case in the Ravine du Butor catchment (16.8 km^2) on 28 February 2025 (fig. 12). The flood was primarily morphogenic starting from Les Cascades downstream of La Convalescence and upstream of the first bridge (D43) in the Providence neighbourhood (fig. 12D). The analysis therefore focused on this 3.5 km-long section (average gradient: 7 %) upstream of the bridge, since downstream, the river had been channelised into concrete sections. On 30 June 2023, the active channel covered 23,763 m^2 with an average width of 7 m, varying from 4 to 25 m (fig. 12E). After Cyclone Belal passed (15 January 2024), the active channel had already widened by 35 %, reaching 32,166 m^2 with an average width of 11 m (ranging from



Riverbanks (total length: 7000 m)							
	LB = Left bank			RB = Right bank			LB + RB
	CV = Convex	CC = Concav	CC + CV	CV	CC	CC + CV	
1		0.4	0.2	2	5.4	3.7	1.9
2				11.5	3.8	7.6	3.8
3	4.5		2.2	5.7	2.4	4.1	3.1
4		4.4	2.2	18	14.7	16.4	9.3
5				4	6.1	5	2.5
6	6.6	16.3	11.4				5.7
7	4.5	3	3.8				1.9
8	84.4	76	80.2	58.8	6.1	5	71.7
%	100	100	100	100	100	100	100

Fig. 12 – Identical reconstruction on riverbanks (Ravine du Butor in Saint-Denis). A: location. B: Ravine du Butor (Saint-Denis) after Cyclone Garance (photo: G. Arnaud-Fassetta, March 21, 2025). The riverbed has been incised by more than a meter, predominantly widening in the concavities, which has caused significant damage to structures and homes. C: Ravine du Butor one year after Cyclone Garance (photo: Zinfos 974 T.L., January 31, 2026). No actions have been taken to increase the cross-section area of the channel, which remains severely undersized, despite the lower (non-human) stakes on the left bank. D: mapping of the banks of Ravine du Butor (the distribution by bank type is expressed as a percentage in the table). E: changes in the width and area of the active channel of the Ravine du Butor between 2023 and 2025.

1- house directly facing the riverbed, 2- garden in front of the house, 3- forest in front of the house, 4- forest in front of the road, 5- forest in front of the parking lot, 6- path in a wooded park, 7- shrubby wasteland, 8- forest, 9- cross-sections taken every 50 m to measure the active-channel width.

Fig. 12 – La reconstruction à l'identique sur les berges (Ravine du Butor à Saint-Denis). *A : localisation. B : la Ravine du Butor (Saint-Denis) après le passage du cyclone Garance (photo : G. Arnaud-Fassetta, 21 mars 2025). Son lit, incisé de plus d'un mètre, s'est surtout élargi dans les concavités, provoquant de lourds dégâts aux structures et aux habitations. C : la Ravine du Butor un an après le passage du cyclone Garance (photo : Zinfos 974 T.L., 31 janvier 2026). Rien n'a été fait pour accroître la section mouillée du chenal, pourtant très insuffisamment dimensionné, alors que les enjeux sont moindres (non humains) sur la rive gauche. D : cartographie des berges de Ravine du Butor (la répartition par type de berge est exprimée en % dans le tableau). E : évolution de la largeur et de la surface de la bande active de la Ravine du Butor entre 2023 et 2025.*

1- maison donnant directement sur le lit de la rivière, 2- jardin devant maison, 3- forêt devant maison, 4- forêt devant route, 5- forêt devant parking, 6- chemin dans parc arborée, 7- friches arbustives, 8- forêt, 9- sections en travers levées tous les 50 m pour la mesure de la largeur de la bande active.

5 to 47 m). Cyclone Garance (28 February 2025) contributed to the greatest expansion, with the active channel reaching an area of 59,031 m^2, an increase of 84 % compared to 15 January 2024, with an average width of 18 m and variations ranging from 6 to 81 m. In total, the active channel of the Ravine du Butor will have expanded by 148 % between 30 June 2023 and 30 March 2025, primarily during the two days when cyclones Belal and Garance made landfall on Réunion Island.

In the section under study, the river has a sinuosity of 1.21, which is not conducive to slowing down floodwaters; on the contrary, it causes flow accelerations in the concavities, which intensify erosion processes (bank scouring, alluvial-floor incision). The most severe damage occurred on the concave sides on 28 February 2025, during the passage of Cyclone Garance (fig. 12 B, D). The peak discharge further downstream at the Butor Bowling station was measured at 375 m^3/s (DEAL). At the study site (fig. 12B), the specific stream power, estimated at 15,269 W/m^2, and the bed shear stress, estimated at 1557 N/m^2, enabled the flows to displace boulders, the largest of which measured 1.38 m (axis b), with a Shields parameter of 0.092. The result was an incision of the alluvial floor by more than one metre and the scouring of the concave riverbanks by 5 to 10 m, damaging homes whose foundations were exposed and walls destroyed. Nearly a year after the flood, bank reinforcement work restored the channel to its original position, while the 2025 flood clearly demonstrated that the cross-section was undersized (fig. 12C). The urgency of the situation justifies rebuilding the channel identically in high-risk areas, but solutions exist within the watershed to increase width in areas where risks are lower and do not involve human populations (fig. 12D).

4.5. A significant portion of the housing in the valley floor

Today, the Réunion Island comprises six territories recognised as areas at significant risk of flooding (TRI). Many of these risk zones are located in the valley floors. Approximately 61 % of the population living in the valley floors is exposed to the risk of flooding. Vulnerability is further exacerbated by the existence of "indecent housing" situated within the flood-hazard zone, which represents between 5 % and 8 % of the housing stock (DEAL; Amri, 2025). However, not all areas within the valley floors of Réunion Island are flood-prone (Arnaud-Fassetta, 2025b), and housing built on alluvial terraces is much less exposed to the risk of flooding compared to that which is constructed within the active channel.

4.5.1. Low to high risk: Housing situated on alluvial terraces

The occupation of alluvial terraces has remained relatively constant since 1950, accounting for 5.5 % of housing in 1950 compared to 5.1 % in 2023 (Amri, 2025). These inhabited alluvial terraces are primarily found in the valleys of the most incised rivers, at the outlets of connecting gorges emerging from cirques, or in the middle and lower parts of the catchments (fig. 2C), such as that of the Rivière des Pluies in Saint-Denis (fig. 13). The catchment area (39 km^2) of the Rivière des Pluies (length: 23 km) cuts more than 1000 m into the volcanic formations of the northern 'planèze' of the Piton des Neiges massif. The river's gradient averages 3 % towards the north from its source (2065 m) to the Indian Ocean, with very steep slopes (30 %) upstream, giving the river a strong incision capacity. In the middle part of the catchment, at the outlet of deep gorges, a system of alluvial terraces develops, often positioned in the convexities created by the river's sinuosity ($S_i = 1.31$). While housing on alluvial terraces is generally safer than in the active channel, residing on an alluvial terrace is not without risk: (*i*) The houses located too close to the slope may be subject to landslides; (*ii*) Although there is typically protection from river flooding, terrace edges can be undermined by significant flood events, damaging or destroying houses built on the alluvial terrace. This was the case opposite the îlet Quinquina during Tropical Storm Diwa (2006), when a house was swept away at the terrace edge (Lucas and Cruchet, 2008).

4.5.2. High to very high risk: housing situated in the active channel

Much more dangerous than living on an alluvial terrace is settling in the active channel of a braided river. Numerous instances of housing constructed within the active channel have, nonetheless, been observed on the Réunion Island. This phenomenon is both historical and recent.

An earlier case of settlement in the active channel can be illustrated through Lazaret No. 2. Located on the right bank of the Ravine de la Grande Chaloupe (length: 7.9 km; catchment area: 5.3 km^2; average slope: 11 %) in the municipality of Saint-Denis (fig. 14A), the buildings of Lazaret No. 2 were constructed from 1863 to increase the quarantine capacity for immigrants (Marimoutou-Oberlé, 2006; Dijoux, 2012; Ferrandis, 2022; fig. 15 A, E). We have monitored the geomorphological evolution of the active channel of the Ravine de la Grande Chaloupe in relation to Lazaret No. 2 between 1950 and 2025 (fig. 14 B-F). The results indicate a significant lateral instability of the river, as well as a high variability in the area and width of the active channel, and in the braiding index. Cyclones have been responsible for the increase in the values of these variables. The active channel has on two occasions (1966-1969 and 1989) been very close (within 8 m) to Lazaret No. 2. Beginning in 2006, a lateral migration of the channel towards Lazaret started, following the shifting of the sinuosity towards the concave bank. This may have been compounded by the effect of a rip-rap on the convex bank upstream, which could have caused flow reflection on the opposite bank (fig. 15G). The partial destruction of Lazaret No. 2 occurred in two phases. In 2024, the channel of the Ravine de la Grande Chaloupe bifurcated during the passage of Cyclone Belal. A progressive channel passed at the foot of the building, excavating a bed of more than a metre that began to undermine the foundations of the first building upstream (fig. 15C). In 2025, the widespread bifurcation of the channel and the significant increase in the width of the active channel resulted in the partial destruction of Lazaret No. 2 (fig. 15D). Never in 163 years had the channel come so close to Lazaret No. 2 (fig. 14F). However, stratigraphic (fig. 15 B, F) and historical data (fig. 15E) attest that Lazaret No. 2 was built on the edges of an active channel that predates the last 163 years, at a similar elevation to the current active channel.

Recent cases (post-1950) of settlements within the active channel are numerous. We will detail two situated in La Possession (Grande Ravine des Lataniers) and Saint-Denis (Rivière Saint-Denis), which were particularly affected by Cyclones Belal and Garance.

The Grande Ravine des Lataniers flows over 10.3 km with an average slope of 8 %. Located in the north-west of the island, its catchment area of 13.3 km^2 was significantly impacted by Cyclone Garance, with hourly rainfall totals (up to 145 mm/h) that would have a return period between 100 and 500 years across the entire catchment, with peaks exceeding 1000 years in the upstream part (Baby, 2025). The geomorphological impacts initially involved the widespread widening of the active channel. On the site known as the Grande Ravine des Lataniers, where the valley floor is urbanised, its average channel width increased from 12 m just before the flood to 35 m immediately thereafter, representing a widening of 188 %. The maximum channel width prior to the flood (19 m) effectively became nearly the minimum channel width after the flood (21 m), with a maximum channel widening of 53 m. Several avulsions then occurred, resulting in the development of channels of reconnections within the active channel (fig. 16). The negative sedimentary balance is also illustrated by bank retreats of nearly 10 m, only slightly offset by accumulations in the form of bars or alluvial spreads, within a context of significant sediment transport. However, it is noted that it takes a look back of 1000 years to observe geomorphological changes in the active channel. A comparison of aerial photographs from 1950 and 2025 shows a markedly different layout of the active channel. Four sites (a-d) heavily impacted (houses destroyed or severely damaged by flooding and/or scouring and/or undermining) in 2025 lie within the footprint of the active channel from 1950. The stratigraphic analysis of the sediments upon which some houses

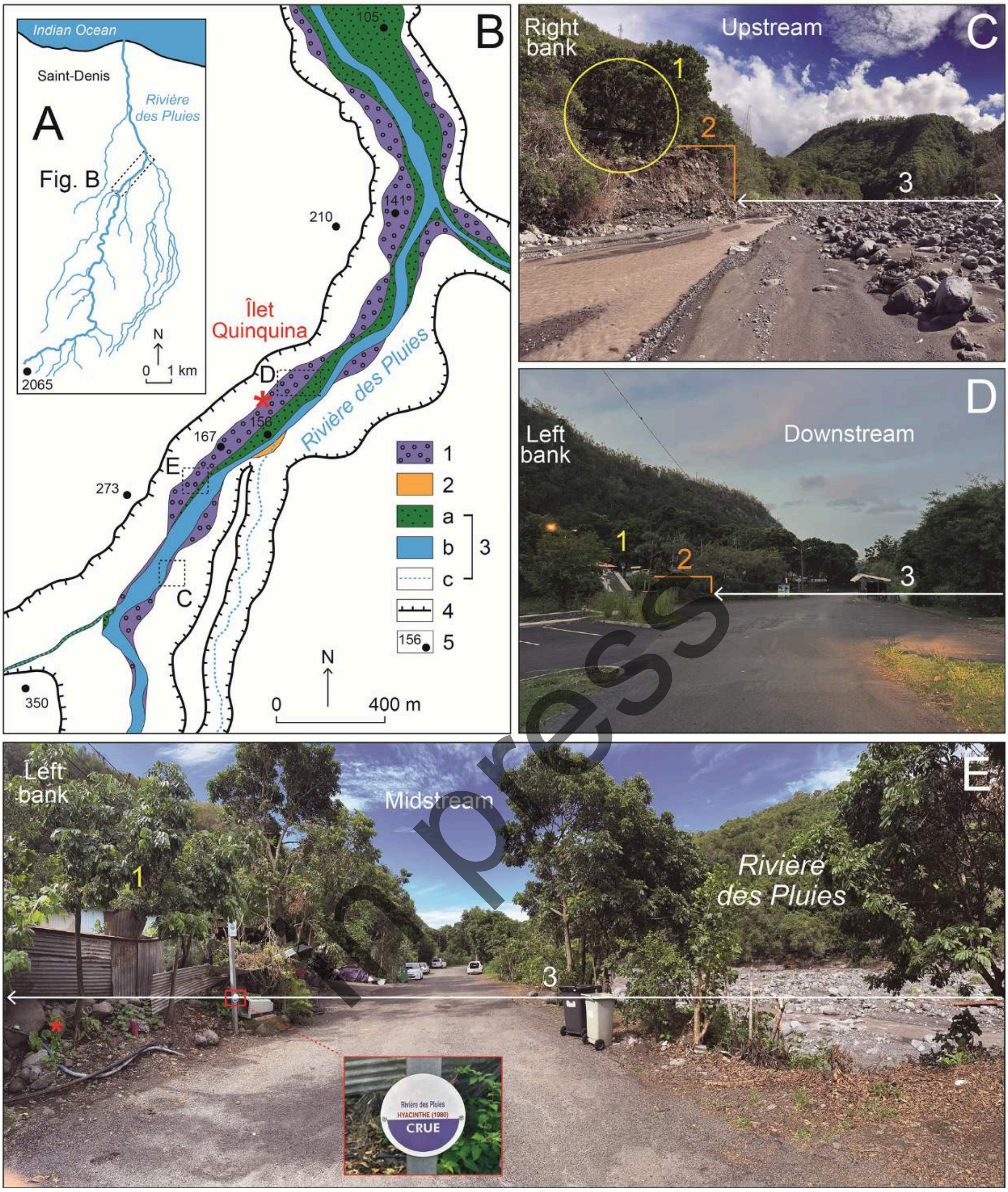


Fig. 13 – Housing built on alluvial terraces (Rivière des Pluies, Îlet Quinquina, Saint-Denis).

A: location. B: mapping of alluvial terraces. 1- urbanised, alluvial terrace, 2- cone-terrace, 3- active channel (a = alluvial bar, b- major channel, c = minor channel), 4- slope, 5- elevation point (in m a.s.l.). C: alluvial terrace constructed in the upstream area on the right bank. This terrace is situated 7 m above the active channel. D: alluvial terrace built in the downstream area on the left bank. This terrace is only 2-3 m above the active channel, the edge of which has been transformed into a parking lot. E: alluvial terrace built in the middle area on the left bank. A few houses are constructed on the alluvial deposits (*), which accumulated at the edge of the active channel during Cyclone Hyacinthe. Other houses, located higher up (not visible in the photo), sit on the alluvial terrace and at the base of the slope. 1- housing, 2- alluvial terrace, 3- active channel.

Fig. 13 – Habitat construit sur les terrasses alluviales (Rivière des Pluies, Îlet Quinquina, Saint-Denis).

A : localisation. B : cartographie des terrasses alluviales. 1- terrasse alluviale urbanisée, 2- cône-terrasse, 3- bande active de tressage (a = banc alluvial, b = chenal majeur, c = chenal temporaire), 4- versant, 5- point coté (en m N.G.F.). C- terrasse alluviale bâtie dans la zone amont, sur la rive droite. La terrasse alluviale domine de 7 m la bande active de tressage. D : terrasse alluviale bâtie dans la zone aval, sur la rive gauche. La terrasse alluviale domine de seulement 2-3 m la bande active de tressage, dont la marge a été aménagée en parking. E : terrasse alluviale bâtie dans la zone médiane, sur la rive gauche. Quelques habitations sont construites sur les alluvions (*) déposées sur la marge de bande active lors du cyclone Hyacinthe). D'autres maisons construites plus en hauteur (non visibles sur la photo) sont sur la terrasse alluviale et le pied de versant. 1- habitat, 2- terrasse alluviale, 3- bande active de divagation ou de tressage.

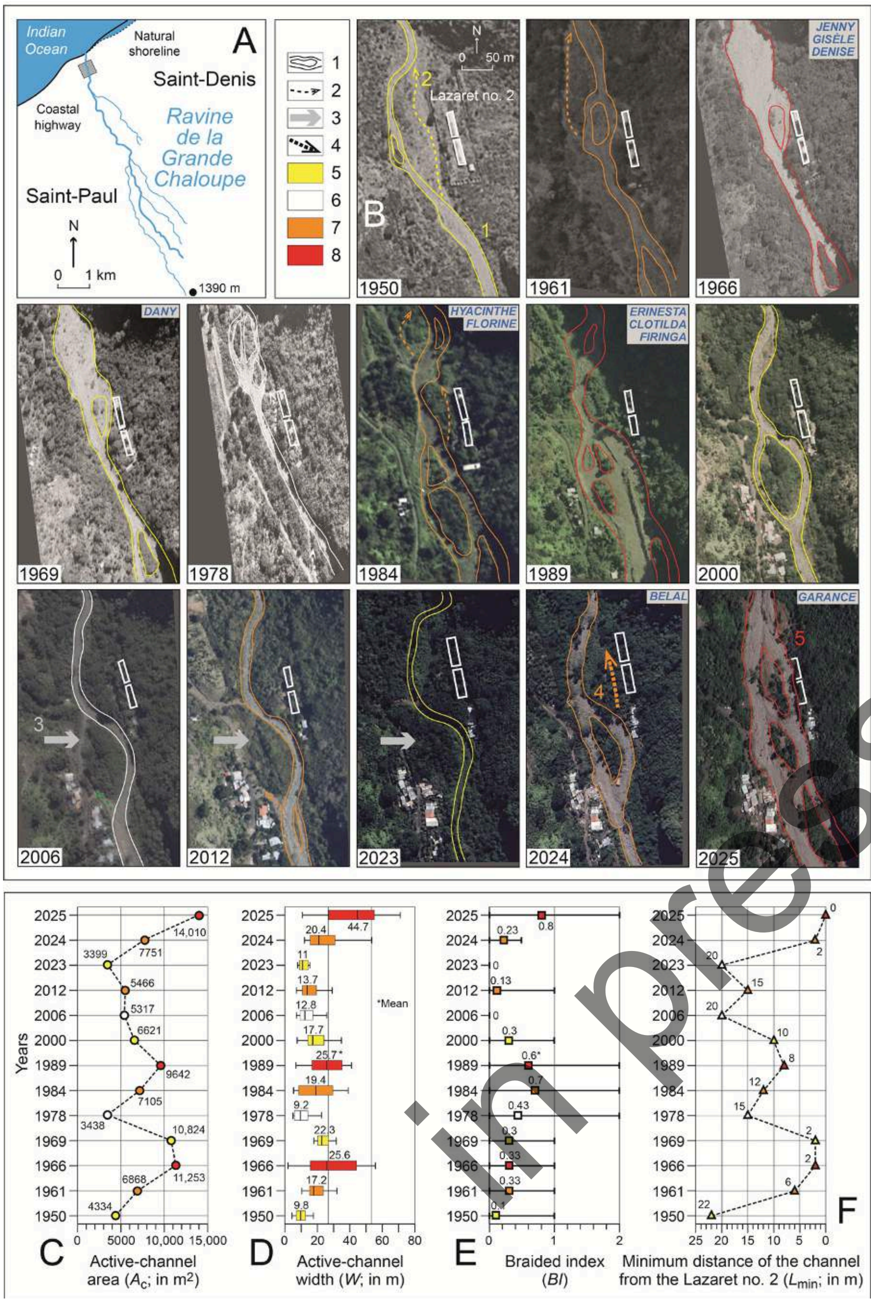


Fig. 14 – Historic construction in the active channel (Lazaret no. 2, Ravine de la Grande Chaloupe, Saint-Denis). A: location. B: diachronic analysis (1950-2025) of the active-channel dynamics in relation to the buildings of Lazaret no. 2. C: evolution of the active-channel area between 1950 and 2025. D: change in the active-channel width between 1950 and 2025. E: change in the braiding index between 1950 and 2025. F: minimum distance between the active channel and the buildings of Lazaret no. 2 between 1950 and 2025. The widening of the active channel during cyclones, combined with the lateral mobility of the channels (primarily natural but possibly exacerbated by human activities upstream), ultimately overwhelmed Lazaret no. 2, which was built 162 years earlier, on February 28, 2025.

1- active channel, 2- regressing channel, 3- lateral migration of the active channel, 4- progressing channel, 5- active channel in the process of narrowing, 6- active channel undergoing significant narrowing, 7- active channel in the process of widening, 8- active channel undergoing significant widening.

Fig. 14 – Construction historique dans la bande active de tressage (Lazaret n°2, Ravine de la Grande Chaloupe, Saint-Denis)*. A : localisation. B : analyse diachronique (1950-2025) de la dynamique de la bande active de tressage par rapport aux bâtiments du Lazaret n°2. C : évolution de la surface de la bande active de tressage entre 1950 et 2025. D : évolution de la largeur de la bande active de tressage entre 1950 et 2025. E : évolution de l'indice de tressage entre 1950 et 2025. F : distance minimale de la bande active par rapport aux bâtiments du Lazaret n°2 entre 1950 et 2025. L'élargissement de la bande active lors du passage des cyclones, associé à la mobilité latérale des chenaux (essentiellement naturelle, mais peut-être aggravée par l'anthropisation du chenal en amont), ont fini par avoir raison, le 28 février 2025, du Lazaret n°2 construit 162 ans auparavant.*

1- bande active de tressage, 2- chenal régressif, 3- migration latérale de la bande active, 4- chenal progressif, 5- bande active en voie de contraction, 6- bande active en forte contraction, 7- bande active en voie élargissement, 8- bande active en fort élargissement.

are built, associated with their topographical position and the level of the highest known waters, confirms that these are gravel units belonging to the active channel either preceding or following 1950 (fig. 16 C, D).

The Rivière Saint-Denis displays an average slope of 3 % along a length of 15.8 km. Located in the north of the island, its catchment area of 31.7 km² (fig. 17A) has similarly recorded significant rainfall totals (a peak of 130 mm/h; Baby, 2025), locally exceeding a return period of 100 to 500 years, and even 500 to 1000 years in the middle part of the catchment. During Cyclone Garance, the flow of the Rivière Saint-Denis reached 613 m³/s at the Saint-Denis Amont station (DEAL). The geomorphological configuration of the valley, characterised by narrow gorges from the L'Entonnoir to the 13 km point, did not allow the river to dissipate its energy laterally through overflows, resulting in the neighbourhood of La Colline, situated at the outlet of the gorges in one of the first sectors where the valley floor begins to widen, regularly suffering damages related to the widening and diversions of the Rivière Saint-Denis. The neighbourhood of La Colline is classified in the red zone of the PPR Saint-Denis (2012) with a hazard rating ranging from low to high concerning flood risk. Thus, the degree of risk in the valley floor is determined by the position of the housing, whether on an alluvial terrace or within the active channel. The geomorphological analysis of the layout of the active channel in La Colline over the period 1950-2025 indicates that almost the entire upstream part of the neighbourhood and its downstream margin lie within the footprint of the active channel of the Rivière Saint-Denis (fig. 17 B-E). The stratigraphic analysis, placed in its topographical and hydraulic context, confirms that these are indeed gravel units belonging to the active channel. On 28 February 2025, the riverbed widened on average by 17 m, increasing from 37 m to 54 m, representing a 45 % increase (fig. 17G). The active-channel area increased in similar

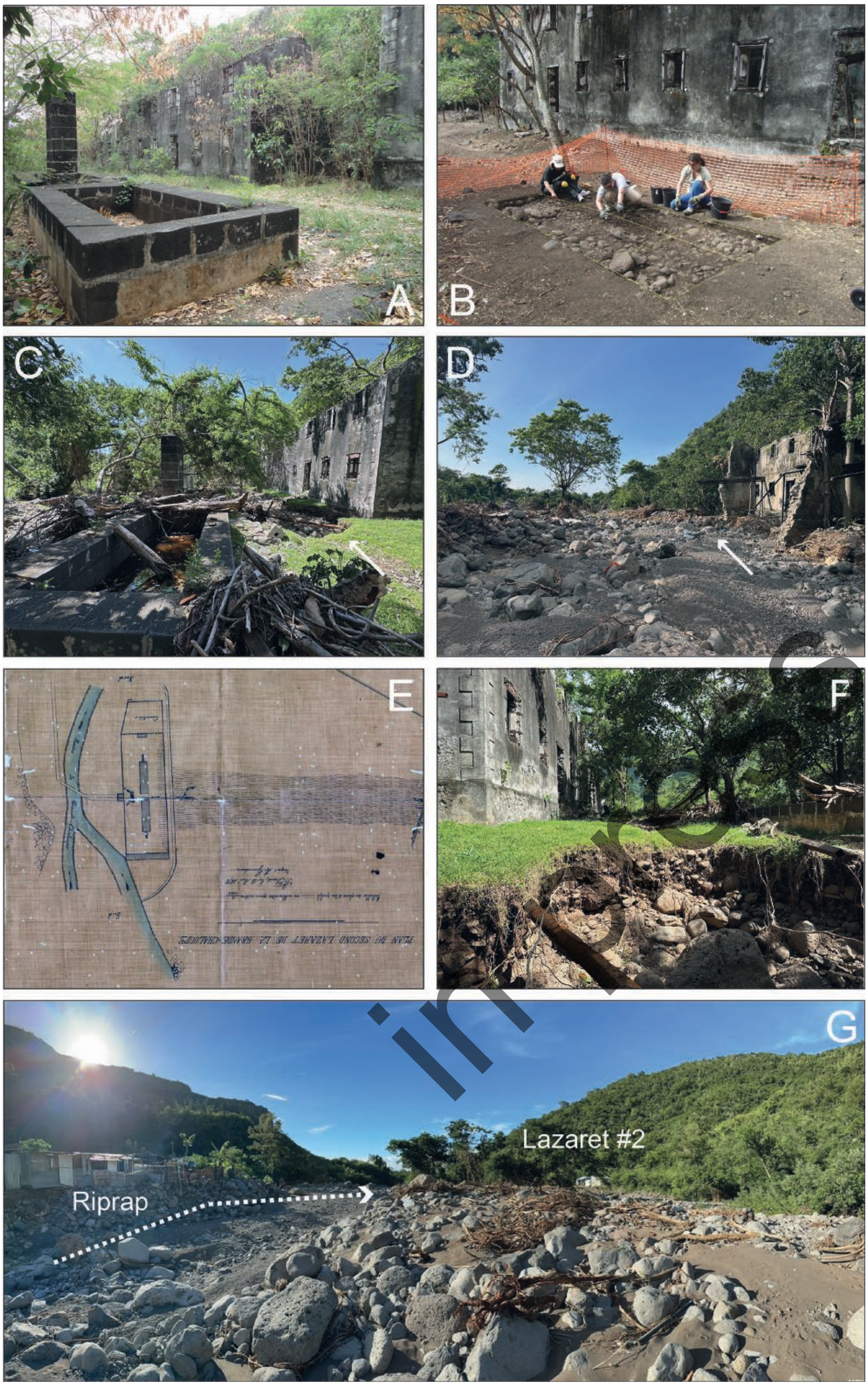


Fig. 15 – Detailed views explaining why Lazaret No. 2 was destroyed by the Ravine de la Grande Chaloupe, Saint-Denis. A: Lazaret No. 2 in 2012 (photo: B. Randoin). B: archaeological excavations in 2012 revealed the coarse alluvium (pebbles with a sparse fine matrix) on which the buildings were constructed starting in 1863 (photo: A.-L. Dijoux). C: the splitting of the Ravine de la Grande Chaloupe, where one of its channels opened up at the base of the buildings during Cyclone Belal (photo: G. Arnaud-Fassetta, February 28, 2024). D: the significant widening of the active channel following Cyclone Garance partially destroyed the buildings (photo: G. Arnaud-Fassetta, March 21, 2025). E: an 1872 plan illustrating the proximity of the split Ravine de la Grande Chaloupe to Lazaret No. 2. The map might (wrongly) give the impression that Lazaret lies outside the ravine's boundaries. F: channel cut on January 15, 2024 (Cyclone Belal) in coarse alluvium (moderately abundant fine-grained pebbles) belonging to the active channel of the Ravine de la Grande Chaloupe. The buildings of Lazaret No. 2 were constructed on this active channel (photo: G. Arnaud-Fassetta, February 28, 2024). G: riprap on the left bank of the channel, which may have caused a slight reflection of the flood wave towards the opposite bank, directing it toward Lazaret No. 2 (photo: G. Arnaud-Fassetta, March 21, 2025).

Fig. 15 – Vues de détail permettant de comprendre les raisons de la destruction du Lazaret n°2 par la Ravine de la Grande Chaloupe, Saint-Denis). *A : le Lazaret n°2 en 2012 (photo : B. Randoin). B : fouilles archéologiques de 2012, permettant d'apercevoir les alluvions grossières (galets à matrice fine peu abondante) sur lesquelles sont construits les bâtiments à partir de 1863 (photo : A.-L. Dijoux). C : dédoublement de la Ravine de la Grande Chaloupe dont l'un des chenaux s'ouvre au pied des bâtiments lors du passage du cyclone Belal (photo : G. Arnaud-Fassetta, 28 février 2024). D : l'élargissement considérable de la bande active de tressage consécutif au passage du cyclone Garance détruit partiellement les bâtiments (photo : G. Arnaud-Fassetta, 21 mars 2025). E : plan de 1872 montrant la proximité entre la Ravine de la Grande Chaloupe (dédoublée) et le Lazaret n°2. Le plan pourrait laisser croire (à tors) que le Lazaret est en dehors de l'emprise de la ravine. F : entaille du chenal du 15 janvier 2024 (cyclone Belal) dans des alluvions grossières (galets à matrice fine moyennement abondante) appartenant à la bande active de tressage de la Ravine de la Grande Chaloupe. Les bâtiments du Lazaret n°2 ont été construits sur cette bande active de tressage (photo : G. Arnaud-Fassetta, 28 février 2024). G : enrochements en rive gauche du chenal, pouvant avoir provoqué une légère réflexion de l'onde de crue vers la rive opposée en direction du Lazaret n°2 (photo : G. Arnaud-Fassetta, 21 mars 2025).*

proportions, rising from 57,579 m^2 in 2024 to 82,948 m^2 in 2025, which corresponds to a 44 % increase (fig. 17F). In 1950, the average width and area values of the active channel, respectively 84,862 m^2 and 51 m, are closely equivalent to those in 2025. The danger is thus, unfortunately, very real and enduring, at least for the upstream part of the neighbourhood, where in addition to houses destroyed by the flood (those situated in the axis of the active channel), three houses were demolished on 24 July 2025 by order of the prefecture and the municipality of Saint-Denis (relocation procedure).

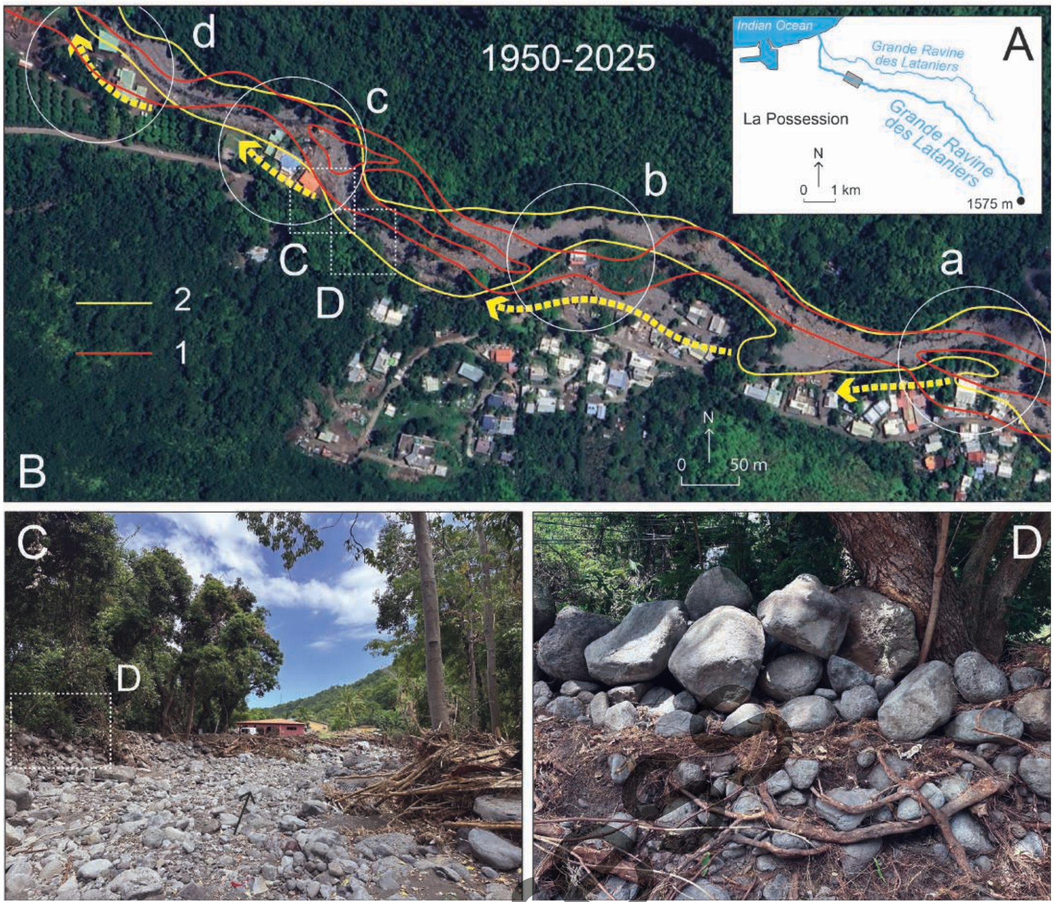


Fig. 16 – Recent construction in the active channel (Grande Ravine des Lataniers, La Possession). A: location. B: diachronic analysis (1950-2025) of the active-channel dynamics. Four sites (a-d) affected in 2025 are located within the 1950 active channel. C: site c. The houses in the background were constructed in the active channel prior to 1950 (photo: G. Arnaud-Fassetta, March 13, 2025). D: detailed view of the deposits (openwork blocks and fine-grained pebbles) that comprise the active channel (photo: G. Arnaud-Fassetta, March 13, 2025).

1- active channel in 1950, 2- active channel on February 28, 2025 (Cyclone Garance).

Fig. 16 – Construction récente dans la bande active de tressage (Grande Ravine des Lataniers, La Possession)*. A : localisation. B : analyse diachronique (1950-2025) de la dynamique de la bande active de tressage. 4 sites (a-d) affectés en 2025 sont dans l'emprise de la bande active de tressage de 1950. C : site c. Les habitations en arrière-plan sont construites dans la bande active de tressage antérieure à 1950 (photo : G. Arnaud-Fassetta, 13 mars 2025). D : vue de détail des dépôts (blocs en openwork et galets à matrice fine peu abondante) constituant la bande active de tressage (photo : G. Arnaud-Fassetta, 13 mars 2025).*

1- bande active de tressage de 1950, 2- bande active de tressage du 28 février 2025 (cyclone Garance).

5. Discussion

The results obtained concerning river dynamics in Réunion Island raise the issue of managing violent and sudden floods in heavily urbanised downstream sections of catchments. The scientific challenges faced by researchers resonate with the initiatives implemented by the DEAL and the structures governed by the GEMAPI law to ensure sustainable management of these catchments.

5.1. Scientific challenges

The challenges associated with managing flood risk in the valley floors of Réunion Island highlight several crucial aspects that require in-depth consideration regarding rapid flood hazards and the vulnerabilities associated with these challenges, particularly in the context of climate change. Geomorphological analysis can contribute to addressing these challenges, complementing engineering and modelling approaches:

- in this study, the geomorphological analysis offers insights into potential long return period floods, which are inadequately represented by simulations alone (Arnaud-Fassetta et al., 2026). On the Réunion Island, field data have allowed for reflections that date back to the 19th century, opening up a sufficiently broad analytical window to interpret the 'geomorphological timeline' of the river (Bravard, 1998). Considering the dynamics of the river over the long term, spanning several decades to a few centuries, helps to better assess risks and their spatial impact;
- respecting the upstream-downstream logic is crucial for effective catchment management (Brierley and Fryirs, 2005; Lalubie, 2010). For example, the reflective effects of bank reinforcements in sinuosities will inevitably exacerbate erosion on the opposite bank (Arnaud-Fassetta et al., 2002, 2005);
- geomorphological analysis has enabled the examination of the inherent dynamics of lateral river mobility, allowing for the anticipation of future damage when housing is poorly sited, typically within the concavities of free or shallowly incised meanders (Becat, 2013);
- for larger rivers, geomorphological analysis has shown the relevance of distinguishing between the active channel and alluvial terraces to

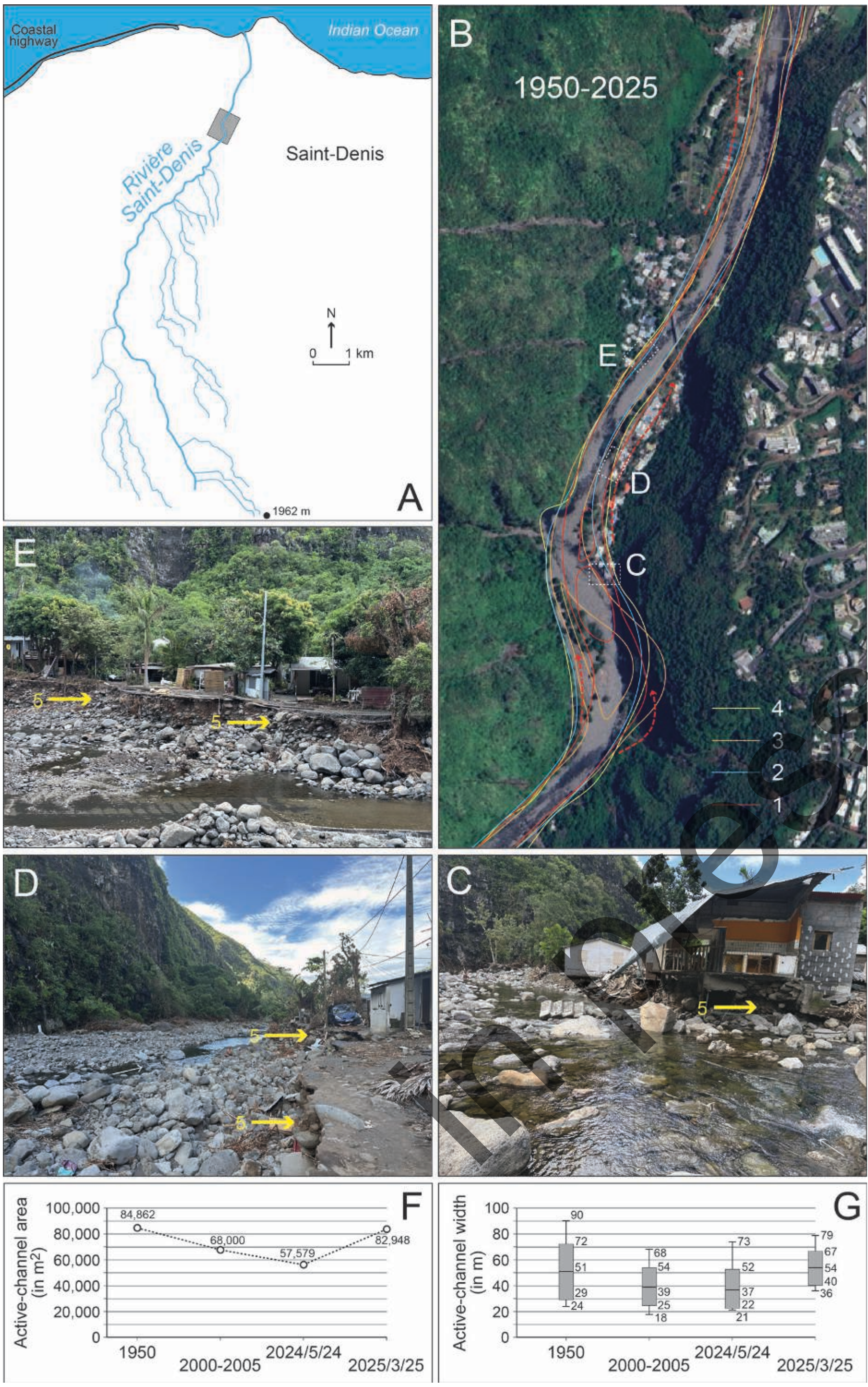


Fig. 17 – Recent construction in the active channel (Rivière Saint-Denis, La Colline, Saint-Denis). A: location. B: diachronic analysis (1950-2025) of the active-channel dynamics. C and D: house built in the 1950-2025 active channel and heavily damaged in 2024 and 2025 (photo: G. Arnaud-Fassetta, March 20, 2025); The houses were demolished on July 24, 2025, on the orders of the prefecture and the municipality. E: houses built on the pebbles of the 1950-2025 active channel (photo: G. Arnaud-Fassetta, March 15, 2025). 5 (yellow arrow): Gravelly sedimentary unit (1950-2025 active channel). F: evolution of the active-channel area between 1950 and 1925. G: evolution of the active-channel width between 1950 and 1925.

1- active channel (1950), 2- active channel (2000-2005), 3- active channel (May 30, 2024), 4- active channel (March 30, 2025).

Fig. 17 – Construction récente dans la bande active de tressage (Rivière Saint-Denis, La Colline, Saint-Denis). *A : localisation. B : analyse diachronique (1950-2025) de la dynamique de la bande active de tressage. C et D : habitation construite dans la bande active de tressage 1950-2025 et lourdement endommagée en 2024 et 2025 (photo : G. Arnaud-Fassetta, 20 mars 2025) ; les maisons ont été rasées le 24 juillet 2025 sur ordre de la préfecture et de la municipalité. E : habitations construites sur les galets de la bande active de tressage 1950-2025 (photo : G. Arnaud-Fassetta, 15 mars 2025). 5 (flèche jaune) : Unité sédimentaire graveleuse (bande active de tressage 1950-2025). F : évolution de la surface de la bande active de tressage entre 1950 et 1925. G : évolution de la largeur de la bande active de tressage entre 1950 et 1925.*

1- bande active de tressage (1950), 2- bande active de tressage (2000-2005), 3- bande active de tressage (30 mai 2024), 4- bande active de tressage (30 mars 2025).

better assess the associated risks in the valley floor. This distinction is an integral part of the hydro-geomorphological mapping of valleys, leading to the development of flood-risk prevention plans (Garry et al., 2002). The creation of accurate geomorphological maps of valley floors in Réunion Island remains to be done. Such maps would be highly beneficial, as the issue of territorial restructuring in the face of flooding is more pertinent than ever on the island;

- in many catchments, river channels suffer from a lack of space as they traverse densely populated urban areas. This situation originates from the implementation of the PPER, which, in the early 1980s, promoted the channelisation of 'ravines', justifying the oversizing of flood control structures. However, this approach has led to an aggravation of flood risk (Lorion, 2013). High-energy rivers of Réunion Island, which are heavily anthropogenically altered, have had their evolutionary trajectories significantly disrupted by these embankments, recalling cases observed in Japan (Dumont et al., 2024) or the Canary Islands (López Díez et al., 2019). In response, hydraulic solutions are now limited regarding the reconsideration of channel width, which is generally inadequate during floods, resulting in the identical reconstruction of 'ravine' edges. Moreover, in many catchments, there is a significant risk associated with residing in valley floors that lack dykes, particularly when no hydraulic solutions can be applied to mitigate the impact of flood events;

- geomorphological analysis demonstrates that sensible solutions exist to avoid or mitigate river or rainfall flooding that may be caused by poorly designed developments. Indeed, rainfall runoff has often appeared exacerbated by infrastructures (roads, bridges), making it relatively easy to resolve. It is also induced by the very design of river dykes, which create impermeable hydraulic enclosures that do not allow for the drainage of runoff water. The installation of backflow preventers in the dykes should be studied to avoid ultimately substituting rainfall risk for flood risk. In the face of rainfall runoff, the cofferdams observed in Salazie, which are ready to be installed at the entrances of houses located on streets with heavy runoff, should certainly be generalised;
- for rivers, should solutions be sought to improve the existing infrastructure, a holistic reflection is necessary to redefine and integrate the dynamics of the "river space" in relation to the "stakes" that must be prioritised (what we wish to protect foremost from floods?). Mapping the EBF – Effective functioning space ("*espace de bon fonctionnement*" in French) would be a solution worth considering (at least for testing) to enhance the integration of the principal functions (geomorphology, hydrogeology, hydrology, hydraulics, biology, biogeochemistry) of the river along with the pressures and anthropogenic uses (Malavoi et al., 1998). Defining and preserving the EBF of a river allows for the (re) integration of the watercourse within the catchment while ensuring management of flood hazards, groundwater recharge, water quality, and green tourism (Terrier and Stroffek, 2016);
- mitigating flood risk in the face of sudden floods predominantly involves reducing vulnerability by addressing the issues at hand (DGPR, 2023; Moulin et al., 2017; Rode, 2022). There is little that can be done to limit the impact of the meteorological hazard and its hydro-geomorphological response (what can be done against the 597 mm of rain brought by Cyclone Garance on 28 February 2025, or against the 1825 mm that fell on 7 January 1966 during Cyclone Denise?);
- the people of Réunion Island need to prepare to transition from centuries of adaptation to the specific climatic conditions (intense rainfall, rapid hydrological response, significant intra-annual and interannual variability on the island scale) to adaptation to climate change, which is already manifesting as a shortened wet season, leading to a stronger concentration of rainfall that is becoming more intense (IPCC, 2023).

5.2. Ongoing work of managers

The hydro-geomorphological observations made earlier fully align with the perspectives of the DEAL, a decentralised service of the French State and a key body in flood-risk prevention on the Réunion Island. The intensification of hydrometeorological hazards observed (IPCC, 2023), characterised by extreme precipitation and exceptionally rapid 'ravine' flooding, is taking place in a region whose systemic vulnerability is now exacerbated by an increasing dependence of Réunion society on technical networks (water, energy, telecommunications) during major crises. Adding to these factors are specific island characteristics: constrained topography that favours very reactive hydrological processes, and an insularity that drastically limits the capacity for rapid external reinforcement.

Recent experiences following cyclones Bélal (2024) and Garance (2025) have confirmed the alarming speed of floods, sometimes leading to the abrupt isolation of entire neighbourhoods in less than two hours and to rapid morphological changes in the beds of ravines. Given the limitations of strictly structural protections, which can generate a false sense of security among residents, the DEAL advocates moving beyond the logic of embankments towards a comprehensive strategy of territorial resilience, based on four fundamental levers:

(i) anticipation and improvement of knowledge: In light of the rapid changes in the hydrographic network, developing a dynamic hydro-geomorphological mapping system is essential. This requires regular geomorphological monitoring of ravines, improvements in modelling flood-prone areas, and strengthened surveillance of flood control systems and hydraulic structures;

(ii) reducing vulnerability: This is the central pivot of the institutional paradigm shift. It relies on adapting building standards, reducing the exposure of critical infrastructure, and, importantly, the gradual and definitive relocation of populations exposed to the most dangerous situations. This approach directly aligns with the geomorphological analysis of this study, acknowledging the inevitable withdrawal of habitat situated within the active channel;

(iii) crisis management and adaptation: The anticipation of preventive evacuations is paramount to cope with the rapid dynamics of flood events. This also involves developing appropriate tools, incorporating scenarios of structural failure into crisis exercises, and designing solutions that ensure the continuity of essential services under degraded conditions;

(iv) cultural awareness and risk culture: The gradual loss of cultural awareness of natural risks among new urban generations poses a major challenge. The DEAL emphasises the importance of active participation from residents, encouraged by the installation of flood markers, targeted preventive information, and the expansion of the awareness programme "Paré pas Paré" (https://pirac.croix-rouge.fr/project/pare-pas-pare/). Cultivating a risk culture also involves organising photographic exhibitions on the history of flooding (Larive and Arnaud-Fassetta, 2025);

6. Conclusions

The people of Réunion Island have adapted early on to climatic constraints and flood risks. Following the adoption of the WFD, Réunion strengthened its water management structures by creating the Water Office and a Basin Committee, which has now evolved into the Committee for Water and Biodiversity, facilitating coherent water governance.

The paper underscores the crucial importance of integrated and proactive flood-risk management in Réunion Island, in the face of increasingly intense and frequent hydrometeorological events. Cyclones Belal and Garance revealed the systemic vulnerabilities of a changing territory, where urbanisation in the valley floors and on the 'planèzes' increases hazards. Although mitigation measures can be implemented, the reduction of vulnerability is essential. Hydro-geomorphological analysis, coupled with an understanding of the temporal and spatial dynamics of risk, is indispensable for establishing effective strategies.

It is imperative to reconsider existing structures, particularly dykes, whose design often does not take rainfall runoff into account, exacerbating flooding. The collected data should encourage managers to rethink policy and operational orientations related to flood risk. Furthermore, the involvement and awareness of local communities in risk management are crucial for effective collective action.

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References

Allemand P., Lajeunesse E., Devauchelle O., Langlois V.J. (2023) – Entrainment and deposition of boulders in a gravel bed river. Earth Surface Dynamics, 11, 1, 21–32. DOI: 10.5194/ESURF-11-21-2023

Amri M. (2025) – Étude de la localisation du bâti sur les unités géomorphologiques, dans un contexte d'inondations récurrentes et de changement climatique, sur l'île de La Réunion depuis 1950. Mémoire du master 2 Géographie, aménagement, environnement, développement (GAED), parcours Dynamique des milieux et risques (DYNARISK), université Paris Cité, 106 p.

Arnaud-Fassetta G. (2008) – Les terrasses fluviales. In (Dewolf Y., Bourrié G. Eds.) Les formations superficielles. Genèse, typologies, classification, paysages et environnements, ressources et risques. Ellipses-Édition Marketing, Paris, 236–243.

Arnaud-Fassetta G. (2022) – Fleuve. Hypergéo, online October 26. https://hypergeo.eu/fleuve-hypergeo/

Arnaud-Fassetta G. (2025a) – Les eaux de La Réunion face aux changements climatiques, entre perceptions sociétales et (in)certitudes scientifiques. L'adaptation en cours d'une île révélée par le terrain, le film de recherche et le documentaire photographique. Bilan du programme Sar-Dyn (2024-2025) du LABEX DYNAMITE. Unpublished report, 6 p.

Arnaud-Fassetta G. (2025b) – Retour d'expérience (2024 – 2025) sur le risque « inondation » à La Réunion suite aux cyclones Belal et Garance. Comité technique risques, DEAL Réunion, Saint-Denis, 9 décembre 2025. https://www.reunion.developpement-durable.gouv.fr/IMG/pdf/5_g._rex_belal_garance_univparis_arnaud-fassetta.pdf

Arnaud-Fassetta G., Beltrando G., Fort M., Plet A., André G., Clément D., Dagan M., Méring C., Quisserne D., Rycx Y. (2002) – La catastrophe hydrologique de novembre 1999 dans le bassin-versant de l'Argent Double (Aude, France) : de l'aléa pluviométrique à la gestion des risques pluviaux et fluviaux. Géomorphologie : relief, processus, environnement, 8, 1, 17–34. DOI:10.3406/morfo.2002.1125

Arnaud-Fassetta G., Cossart É., Fort M. (2005) – Hydro-geomorphic hazards and impact of man-made structures during the catastrophic flood of June 2000 in the Upper Guil catchment (Queyras, French Alps). Geomorphology, 66, 41–67. DOI: 10.1016/j.geomorph.2004.03.014

Arnaud-Fassetta G., Larive J., Amri M., Taglioni F., Lorion D., Méchain A., Dahech S. (2025) – Adaptation to flood risk on Réunion Island (France): A historical perspective from mapping and photographic evidence. Poster presented on April 28, 2025, during session HS7.5 - Hydro-Meteorological Extremes and Hazards: Vulnerability, Risk, Impacts, and Mitigation at the EGU (European Geosciences Union) General Assembly 2025 in Vienna (Austria), under identification number EGU25-6246.

Arnaud-Fassetta G., Brun M., Dupuis M., Bellon T., Perrine L., Brousse B., Fort M. (2026) – When geomorphological field data and systemic analysis help refine the uncertainties of numerical hydrometeorological models in extreme values. Case study: The catastrophic flood event of October 14-15, 2018, in the Aude watershed (southern France). Géomorphologie: relief, processus, environnement, 32, 1. DOI:10.4000/15rpd

Baby F. (2025) – Réunion – Cyclone Garance. Retour d'expériences suite au passage du cyclone. Phase 1 : reconnaissances terrain et premières analyses post-cyclone. Rapport CEREMA, 94 p.

Baby F., Boujard P., Martel S., Roulenq A., Villani D., Organde D., Javelle P., Tilmant F., Perrin C. (2024) – Prévision des crues en milieu montagneux sous climat tropical : exemple de La Réunion. LHB: Hydroscience Journal, 110,1, 2374540. DOI: 10.1080/27678490.2024.2374540

Bagnold R.A. (1966) – An approach to the sediment transport problem from general physics. U.S. Geological Survey professional paper, 422, 1–37. DOI: 10.3133/pp422I

Barcelo A., Robert R., Coudray J. (1997) – A major rainfall event: The 27 February-5 March 1993 rains on the southeastern slope of Piton de la Fournaise massif (Reunion Island, Southwest Indian Ocean). American Meteorological Society, Notes and correspondence, Monthly weather review, 125, 3341–3346.

Becat J. (2013) – Aiguats et inondations exceptionnelles en Andorre au XX^e^ siècle. RECERC, Ouvrages de reference, Collection Andorre, 5. ICRESS, Institut catalan de recherche en sciences sociales (EA 3681), Université de Perpignan Via Domitia, 165 p.

Beerbower J.R. (1964) – Cyclothems and cyclic depositional mechanism in alluvial plain sedimentation. Kansas Geological Survey Bulletin, 169, 35–42.

Bocquée F., Givone P. (1980) – Esquisse hydrométérologique des effets du cyclone Hyacinthe sur le département. Département de La Réunion, Direction départementale de l'agriculture, Service de l'aménagement hydraulique, 14 p.

Bourquin A. (2005) – Histoire des Petits-Blancs de La Réunion, XIXe-début XXe siècles. Éditions Karthala, Paris, 327 p.

Bravard J.P. (1998) – Le temps et l'espace dans les systèmes fluviaux, deux dimensions spécifiques de l'approche géomorphologique. Annales de géographie, 107, 599, 3–15. DOI: 10.3406/geo.1998.20830

Bravard J.P., James A., Pagney Bénito-Espinal F. (2001) – Les effets des glissements de terrain sur la morphodynamique fluviale dans le bassin de la Layou (La Dominique, Antilles). Géomorphologie: relief, processus, environnement, 7, 4, 257–270. DOI: 10.3406/morfo.2001.1110

Brierley G.J., Fryirs K.A. (2005) – Geomorphology and river management: Applications of the river styles framework. Blackwell Publishing, Oxford, 398 p. DOI: 10.1002/9780470751367

Cadet F. (Ed.) (2003) – Atlas de La Réunion. Université de La Réunion / INSEE, 143 p.

Chetoui C. (2019) – Sécurisation de la RN5 (route du Cilaos, secteur Les Aloès / Îlet Furcy, PR6+000 au PR12+200. Mission

Complémentaire n° 1 : actualisation de l'étude hydraulique (MC1) APSIQ 2010 et analyse des variants. Rapport EGIS, 280 p.

Compain J.D. (2006) – 350 ans d'architecture à l'île de La Réunion. CAUE Réunion, Saint-Denis, 207 p.

CNRS/IGN (1975) – Atlas des Départements français d'Outre-Mer. I. La Réunion. CNRS, Paris.

Combeau Y. (2022) – Histoire de La Réunion. Que sais-je, Paris, 126 p.

Desarthe J., Moncoulon D. (2017) – Quatre siècles de cyclones tropicaux dans les départements français d'outre-mer. La Météorologie, 99, 52–58. DOI: 10.4267/2042/63590

DGPR (2023) – Guide méthodologique pour l'élaboration des plans de prévention des risques d'inondation des cours d'eau torrentiels. MTECT, 126 p.

Dijoux A.L. (2012) – Saint-Denis – La Grande Chaloupe, Lazaret n°2. Archéologie de la France – Informations, Océan Indien et TAAF, 18 p.

Du Boys M.P. (1879) – Études du régime du Rhône et de l'action exercée par les eaux sur un lit à fond de graviers indéfiniment affouillable. Annales des Ponts et Chaussées, 5, 18, 141–195.

Dumont M., Arnaud-Fassetta G., Gomez C., Lissak C., Viel V. (2023) – From the hydroclimatic disaster to the forced (re) construction: Case study of the Akatani watershed in Japan. Proceedings, 87, 42. DOI:10.3390/IECG2022-14820

Dumont M., Siccard V., Arnaud-Fassetta G., Gomez C., Lissak C., Viel V. (2024) – Mutations paysagères dans la région Nord de Kyūshū (Japon) induites par les pluies torrentielles de juillet 2017 et les projets de restauration associés. Géomorphologie: relief, processus, environnement, 30, 4. DOI: 10.4000/13tov

Dupont M., Villeneuve N., Rault C., Chaput M. (2026) – Perceptions et représentations de la gestion du risque cyclonique à La Réunion : les cas de 1980, 2018 et 2024. Cybergeo: European Journal of Geography, 1104, 30 p. DOI: 10.4000/15zea

Duvoisin J. (1994) – La Réunion "L'endiguement des grandes ravines sur leur cône de dejection". Crues et inondations. 23e journées de l'hydraulique, Congrès de la Société hydrotechnique de France, Nimes (France), 14-16 septembre 1994, Tome 2, 413–419.

Ferrandis M. (2022) – Saint-Denis – Lazaret 2, Grande Chaloupe. Archéologie de la France – Informations, Océan Indien et TAAF, 8 p.

Folton N. (2024) – Using spot flow measurements in a regionalized hydrological model to improve the low flow statistical estimations of rivers: The case of Réunion Island. Journal of Hydrology: Regional Studies, 52, 101730. DOI: 10.1016/j.ejrh.2024.101730

Fort M., Gurung N., Yvrard P., Bell R., Burrows K., Rimal B., Arnaud-Fassetta G. (2025) – The Kagbeni flood event (August 13, 2023), Mustang District (Nepal): Triggers, sediment cascades, aggravating infrastructures and disaster risk management. Géomorphologie : relief, processus, environnement, 31, 4. DOI: 10.4000/154u

Fuma S. (2004) – Archéologie et histoire pour comprendre l'esclavage et le marronnage à La Réunion au XVIIIe siècle. Travaux & documents, 21, 127–137.

Galewsky J., Stark C.P., Dadson S., Wu C.C., Sobel A.H., Horng M.J. (2006) – Tropical cyclone triggering of sediment discharge in Taiwan. Journal of Geophysical Research, 111, F03014. DOI:10.1029/2005JF000428

Garnier E. (2014) – Cyclones et sociétés dans les Mascareignes XVIIe-XVIIIe siècle. Revue historique de l'océan Indien, 11, 229–247.

Garry G., Ballais J.L., Masson M. (2002) – La place de l'hydrogéomorphologie dans les études d'inondation en France méditerranéenne. Géomorphologie : relief, processus, environnement, 8, 1, 5–15. DOI: 10.3406/morfo.2002.1124

Gaume E., Borga M., Llasat M.C., Maouche S., Lang M., Diakakis M. (2016) – Mediterranean extreme floods and flash floods. In ALLENVI (Ed.) The Mediterranean Region under Climate Change. A Scientific Update. IRD Éditions, Marseille, 133–144.

Gayer É., Michon L., Louvat P., Gaillardet J. (2019) – Storm-induced precipitation variability control of long-term erosion. Earth and Planetary Science Letters, 517, 61–70. DOI: 10.1016/j.epsl.2019.04.003

Gayer É., Lucas A., Michon L., Gougeon M. (2025) – Evidence for erosional efficiency of extreme precipitation events at a multi-decadal timescale. Journal of Geophysical Research: Earth Surface, 130. DOI: 10.1029/2024JF007818

Germanaz C. (2011) – Cartographier Bourbon aux XVIIe-XIXe siècles. Voyage cartographique dans l'une des quatre principales îles des mers de l'Afrique, Bourbon Lontan. CFC, 210, 107–118.

Germanaz C. (2016) – Un tour des cartes de Bourbon. Matériaux pour une histoire de la representation cartographique de La Réunion. Bulletin de l'Académie de l'Île de La Réunion, 32, 47–73.

Gillot P.Y., Lefèvre J.C., Nativel P.E. (1994) – Model for the structural evolution of the volcanoes of Réunion Island. Earth and Planetary Science Letters, 122, 291–302. DOI: 10.1016/0012-821X(94)90003-5.

Gonzalez A., Fontaine F.R., Barruol G., Recking A., Burtin A., Join J.L., Delcher É., Michon L., Gimbert F. (2023) – Seismic signature of a river flooding in La Réunion Island during the tropical cyclone Dumazile (March 2018). Journal of Applied Geophysics, 215, 105127. DOI: 10.1016/j.jappgeo.2023.105127

Gurung N., Fort M., Bell R., Arnaud-Fassetta G., Raj Maharjan N. (2021) – Hydro-torrential hazard vs. anthropogenic activities along the Seti valley, Kaski, Nepal: Assessment and recommendations from a risk perspective. Bulletins of Nepal Geological Society, 62, 58–87. DOI: 10.3126/jngs.v62i0.38695

Hoarau L. (2012) – Caractérisation des phénomènes historiques et synthèse bibliographique. Rapport non publié, 61 p.

Howard A.D., Keetch M.E., Vincent C.L. (1970) – Topological and geomorphic properties of braided streams. Water Resources Research, 6, 1647–1688. DOI: 10.1029/WR006i006p01674

Ikhsan J., Wardhana C., Widiyarto D.K. (2019) – Sediment characteristics of bed load transport in downstream of Progo River, Indonesia. IOP Conference Series: Materials Science and Engineering, 650, 012062. DOI:10.1088/1757-899X/650/1/012062

IPCC (2023) – Climate change 2023: Synthesis report. Contribution of working groups I, II and III to the Sixth assessment report of the intergovernmental panel on climate change [Core Writing Team, H. Lee and J. Romero (Eds.)].

Join J.L., Coudray J., Longworth K. (1997) – Using principal components analysis and Na/C1 ratios to trace groundwater circulation in a volcanic island: The example of Reunion. Journal of Hydrology, 190, 1–18. DOI: 10.1016/S0022-1694(96)03070-3

Jumaux G., Quetelard H., Roy D. (2011) – Atlas climatique de La Réunion. MétéoFrance, Sainte-Clotilde.

Lalubie G. (2010) – Les cours d'eau du massif de la Montagne Pelée : une approche multiscalaire pour apprehender les risques hydro-volcano-géomorphologiques. Thèse de géographie, université des Antilles et de la Guyane, 318 p.

Larive J., Arnaud-Fassetta G. (2025) – Observatoire photographique spécifique des zones à risque de La Réunion. Photography exhibition, CCSTI Sciences Réunion, 3-4 October 2025, Jardin de la Médiathèque F. Mitterrand, Saint-Denis, 20 posters with commentary.

Lavigne F., Thouret J.C. (2003) – Sediment transportation and deposition by rain-triggered lahars at Merapi Volcano, Central Java, Indonesia. Geomorphology, 49, 1-2, 45–69. DOI: 10.1016/S0169-555X(02)00160-5

Lénat J., Gibert-Malengreau B., Galdéano A. (2001) – A new model for the evolution of the volcanic island of Reunion (Indian Ocean). Journal of Geophysical Research: Solid Earth, 106, 8645–8663. DOI: 10.1029/2000JB900448.

Léone F. (2026) – Mortalité et aléas hydro-climatiques dans les Outre-mer français : spécificités réunionnaises et pistes de prevention. Comité technique risques, DEAL Réunion, Saint-Denis, 26 février 2026.

López Díez A., Máyer Suárez P., Díaz Pacheco J., Dorta Antequera P. (2019) – Rainfall and flooding in coastal tourist areas of the Canary Islands (Spain). Atmosphere, 10, 809, 20 p. DOI: 10.3390/atmos10120809

Lorion D. (1995) – Les risques d'inondation sur la Planèze des Cabris à l'île de la Réunion. Bulletin de l'Association de Géographes Français, 72, 4, 342–349. DOI: 10.3406/bagf.1995.1848

Lorion D. (1999) – Les crues et les divagations torrentielles, entre fatalité et prévention. Prévision et surveillance des crues torrentielles de l'île de La Réunion. Travaux & documents, Propos géographiques sur le Sud-Ouest de l'océan Indien, 11, 69–82.

Lorion D. (2006) – Endiguements et risques d'inondation en milieu tropical. L'exemple de l'île de La Réunion. Norois, 201, 4, 45–66. DOI: 10.4000/norois.1753

Lorion D. (2013) – From a utopia of security to the integrated management of drainage basins: The example of Reunion Island (France). In Arnaud-Fassetta G., Masson E., Reynard E. (Eds.) European Continental Hydrosystems under Changing Water Policy. Friedrich Pfeil Verlag, München, 87–98.

Lucas E., Cruchet M. (2008) – Étude géomorphologique de la Rivière des Pluies. Rapport BRGM/RP-56311-FR, 62 p.

Malavoi J.R., Bravard J.P., Piégay H., Hérouin É., Ramez P. (1998) – Guide technique N° 2. Détermination de l'espace de liberté des cours d'eau. Agence de l'eau, 39 p.

Marimoutou-Oberlé M. (2006) – Les lazarets de la Grande Chaloupe : une nouvelle approche dans la prévention des maladies contagieuses à l'île de La Réunion au milieu du XIX[e] siècle ? Revue historique l'Océan Indien, 2, 110–124.

Martín-Vide J.P., Bateman A., Berenguer M., Ferrer-Boix C., Amengual A., Campillo M., Corral C., Llasat M.C., Llasat-Botija M., Gómez-Dueñas S., Marín-Esteve B., Núñez-González F., Prats-Puntí A., Ruiz-Carulla R., Sosa-Pérez R. (2023) – Large wood debris that clogged bridges followed by a sudden release. The 2019 flash flood in Catalonia. Journal of Hydrology: Regional Studies, 47, 101348. DOI: 10.1016/j.ejrh.2023.101348

Métivier F. (2003) – Des sources aux océans, enjeux et problématiques en géomorphologie fluviale. Dossier d'habilitation à diriger des recherches, université Paris-Diderot (Paris 7), 118 p.

Moulin C., Faytre L., Bauduceau N. (2017) – Réduire la vulnérabilité des territoires aux inondations : évaluer pour agir. Sciences Eaux & Territoires, 23, 12–17.

Observatoire réunionnais de l'eau (1993) – Le cyclone tropical Colina et les événements hydrologiques majeurs du 1[er] trimestre 1993. Conseil Général de La Réunion, Saint-Denis, 55 p. + annexes.

Osterkamp W.R., Hedman E.R. (1982) – Perennial-streamflow characteristics related to channel geometry and sediment in Missouri River basin. United States Geological Survey Professional Paper, 1242. DOI: 10.3133/pp1242

Pardé M. (1957) – Quelques aspects saillants et nouveaux de l'hydrologie de la France d'outre-mer. La Houille Blanche, 43, 2, 158–180. DOI: 10.1051/lhb/1957031

Perdreau N. (1969) – Rapport V.12. Études sur modèles réduits de l'endiguement de la Rivière des Pluies et de la Ravine des Patates à Durand sur leur cône de déjection à l'île de La Réunion. La prévision des crues et la protection contre les inondations. Dixièmes journées de l'hydraulique. Paris, 5-7 juin 1968. Tome 5.

Pignon G., Rebeyrotte J.F. (2020) – Esclavage et marronnages. Refuser la condition servile à Bourbon (île de La Réunion) au XVIII[e] siècle. Riveneuve, Paris, 184 p.

Richards K. (1982) – Rivers: form and processes in alluvial rivers. Methuen, London, 358 p.

Rode S. (2022) – Recomposer les territoires pour les adapter aux effets de la crise climatique : l'après-catastrophe comme opportunité pour une meilleure habitabilité ? Sud-Ouest européen, 54, 55–75. DOI: 10.4000/12g5d

Roux S. (2021) – Expertise transport solide préalable à l'EDD de l'endiguement de protection de l'aéroport Roland Garros contre les crues de la Rivière des Pluies. Rapport d'étude I.01101.001 – CACOH 21-503_01 pour le compte de la DEAL Réunion – Service Eau et Biodiversité. CNR Engineering, Lyon, 48 p.

Rundle A. (1985) – Braid morphology and the formation of multiple channels; the Rakaïa, New Zealand. Z. f. Geomorph. N. F., Suppl.–Bd. 55, 15–37.

Salvany T., Lahitte P., Nativel P., Gillot P.Y. (2012) – Geomorphic evolution of the Piton des Neiges volcano (Réunion Island, Indian Ocean): Competition between volcanic construction and erosion since 1.4 Ma. Geomorphology, 136, 132–147. DOI: 10.1016/j.geomorph.2011.06.009

Sellier D. (2016) – Une sélection de géomorphosites dans l'île de La Réunion en fonction de critères morphodynamiques. Physio-Géo, 10, 105–133. DOI: 10.4000/physio-geo.4823

Shields A. (1936) – Anwendung der Aehnlichkeitsmechanik und der turbulenzforschung auf die geschiebebewegung, Technischen Hochschule, Berlin.

Stumpf A., Augereau E., Delacourt C., Bonnier J. (2016) – Photogrammetric discharge monitoring of small tropical mountain rivers: A case study at Rivière des Pluies, Reunion

Island, Water Resources Research, 52, 4550–4570. DOI: 10.1002/2015WR018292

Terrier B., Stroffek S. (2016) – Délimiter l'espace de bon fonctionnement des cours d'eau. Guide technique du SDAGE, Bassin Rhône-Méditerranée, 181 p.

Tolentino P.L.M., Williams R.D., Hurst M.D. (2025) – Natural flood risk management in tropical Southeast Asia: Prospects in the biodiverse Archipelagic Nation of the Philippines. Wiley Interdisciplinary Reviews: Water, 12, 1, 21 p. DOI: 10.1002/wat2.70000

Villeneuve N., Bachèlery P. (2006) – Revue de la typologie des éruptions au Piton de La Fournaise, processus et risques volcaniques associés. Cybergeo: European Journal of Geography, Environnement, Nature, Paysage, document 336. DOI: 10.4000/cybergeo.2536

Version française abrégée

La géomorphologie fluviale française a principalement étudié les cours d'eau en métropole, laissant de côté les territoires d'outre-mer comme La Réunion, où les « rivières » et « ravines » de haute énergie nécessitent une gestion adaptée face à la fréquence accrue d'événements hydrométéorologiques intenses, exacerbés par le changement climatique (fig. 1). La prévention des inondations sur l'île de La Réunion est assurée avec efficacité par un service déconcentré de l'État français, la DEAL – Direction de l'environnement, de l'aménagement et du logement, mais la population croissante accroît le risque inondation. L'article évalue l'impact des cyclones récents, Belal (2024) et Garance (2025), qui ont causé des pertes humaines et des dégâts matériels considérables. Il propose des solutions basées sur une approche systémique et hydro-géomorphologique pour atténuer ce risque, tout en soulignant les difficultés de réaménagement dues aux erreurs passées dans l'aménagement des cours d'eau.

La Réunion est une île française située dans l'océan Indien, caractérisée par une géomorphologie volcanique et un climat subtropical (fig. 2). Avec une surface de 2512 km^2 et une population de 889.679 habitants, elle présente un relief montagneux formé de deux massifs volcaniques principaux : le Piton des Neiges (3070 m), un volcan dormant, et le Piton de la Fournaise (2631 m), actif. Les deux massifs montagneux sont séparés par deux plateaux orientés NE-SW : la Plaine des Palmistes et la Plaine des Cafres. L'intérieur de l'île est creusé par les trois cirques de Mafate, Cilaos et Salazie, qui sont dus à l'affaissement des chambres magmatiques de l'ancien cratère du Piton des Neiges et aux processus d'érosion (glissements de terrain, torrentialité). L'évacuation des produits de l'érosion des cirques est assurée par de vigoureuses rivières qui ont creusé de profondes gorges de raccordement par où transitent des volumes extraordinaires de sédiment constituant des cônes-deltas à leur arrivée sur le littoral. Sur les planèzes, les cours d'eau sont relativement moins encaissés et adoptent le plus souvent une disposition radiale. Sur l'île, la distribution des précipitations est très hétérogène, avec des records atteignant 12 000 mm/an à l'est, générant des rivières puissantes, très instables et, au final, dangereuses (fig. 3). La prévention des inondations est gérée par la DEAL, qui doit composer avec un lourd « héritage », celui de l'endiguement des ravines (PPER) mis en place dans les années 1960 à 1980 (fig. 4). Cette politique d'endiguement a accru la vulnérabilité en favorisant des constructions dans les zones à risque. Aujourd'hui, six territoires de l'île sont classés à risque inondation important (TRI).

Cette étude propose, par une approche pluridisciplinaire, d'intégrer des données multicritères pour analyser la dynamique des rivières et leur relation avec l'occupation du sol à La Réunion. La collecte des données inclut une recension de la littérature existante, avec 279 documents consultés, complétés par des travaux d'historiens locaux. Les sites Google Earth et IGN ont été utilisés pour réaliser une analyse diachronique des photographies aériennes sur la période 1949-2025. En outre, des archives historiques et stratigraphiques ont permis de retracer les événements hydrométéorologiques et leurs impacts. Trois missions de terrain ont été menées en 2024-2025, abordant les impacts des cyclones Belal et Garance sur la dynamique fluviale. Les aléas hydrométéorologiques ont été étudiés sur différents pas de temps, aboutissant à une quantification de la dynamique des bandes actives de tressage réalisée par du suivi de variables géomorphologiques (surface, largeur moyenne, indice de tressage, indice de sinuosité) et hydrauliques (puissance spécifique, force tractrice). Un gros travail a été effectué sur le terrain pour distinguer bande active et terrasse alluviale (fig. 5). Des analyses ont été approfondies pour comprendre le lien entre les unités géomorphologiques, les rivières qui les drainent, l'évolution de l'habitat, la population et les structures. Des photographies aériennes ont permis d'identifier les vulnérabilités sur le bord des rivières, complétées par les enquêtes de terrain, qui ont permis de corréler les réalités scientifiques des crues aux perceptions locales.

Les résultats de l'étude sont les suivants :

- une installation historique sur quatre types d'unités géomorphologiques. L'île de La Réunion est exposée à un risque inondation significatif depuis le début de sa colonisation entre 1638 et 1646, avec une population ayant crû de 12 habitants en 1646 à 881 348 en 2022 (fig. 6). L'île subit régulièrement des cyclones, ayant enregistré 162 tempêtes depuis le XVII^e siècle, entraînant des pertes humaines et des dommages matériels. L'habitat a évolué sur les unités géomorphologiques : les planèzes ont toujours été le lieu privilégié pour l'installation (58 % à 81 %) et la densification de l'habitat, parallèlement à l'augmentation significative de la population, a accru le risque de ruissellement urbain et d'inondation torrentielle, en particulier en ce qui concerne les petits cours d'eau ; les versants, y compris les terrasses alluviales, n'ont jamais représenté plus de 16 % de l'habitat de l'île, mais la population a été multiplié par trois entre 1950 et 2022 ; dans les fonds de vallée, l'occupation est passée de 7 à 11 % dans les premières années à 18 % aujourd'hui, soit 160.204 personnes dont 61 % sont exposées au risque inondation ; les plaines côtières ont connu un déclin constant de l'habitat, passant de 29 % en 1700 à seulement 5 % en 2022. Cependant, en valeurs absolues, la population a atteint un niveau record, avec 44.738 habitants en 2022 ;
- sur les planèzes et les cônes torrentiels, l'étude met en évidence la non prise en compte de la mobilité latérale des cours d'eau (Ravine de la Veuve ; fig. 7), le sous-calibrage des « petits » cours d'eau (Ravine Montplaisir ; fig. 8) associé à des défluviations (Ravine des Citrons Galets ; fig. 9) et la non prise en compte de l'écoulement pluvial (Rivière Saint-Denis ; fig. 12) ;
- dans les fonds de vallée, des digues censées « sécuriser » (fig. 10). L'endiguement des rivières à La Réunion, commencé aux XVIII-XIX^e siècles, a été intensifié par le PPER de 1984, souvent en contradiction avec les PER/PPR. Les digues, conçues pour contenir

les inondations, ne prennent pas en compte le ruissellement urbain, entraînant de graves inondations en ville ;

- la reconstruction à l'identique sur les bords de rivière. Les inondations causées par les cyclones Belal et Garance en 2025 ont nécessité des réparations d'urgence (Ravine du Butor ; fig. 11). L'urgence justifie la reconstruction à l'identique localement sur des sites à forts enjeux, mais des solutions existent dans le bassin-versant pour accroître un peu la largeur des chenaux de rivière, sur des sites où les enjeux sont moindres, non humains (fig. 11D) ;

- une part non négligeable de l'habitat dans le fond de vallée. Parmi les 61 % d'habitants des fonds de vallée exposés à un risque inondation important, les plus vulnérables sont ceux vivant dans des conditions de logement « indignes ». Si l'habitat sur les terrasses alluviales est moins exposé (Rivière des Pluies, fig. 13), il n'est pas exempt de risque (glissement de terrain, sapement de berge). L'installation de l'habitat dans la bande active des rivières exacerbe le risque, avec des dizaines de cas notés, dont trois sont plus particulièrement documentés (Ravine de la Grande Chaloupe, fig. 14 et fig. 15) ; Grande ravine des Lataniers, fig. 16 ; Rivière Saint-Denis, fig. 17).

Les résultats obtenus concernant la dynamique des rivières à La Réunion soulèvent la problématique de la gestion des crues violentes et soudaines dans des bassins versants fortement urbanisés en aval. (*i*) L'analyse géomorphologique montre la nécessité de mobiliser les données de terrain, sur les temps de retour de l'événement, en plus de la simulation. (*ii*) Le respect de la logique amont-aval est crucial pour une gestion efficace des bassins versants. (*iii*) L'analyse géomorphologique a permis d'analyser la dynamique inhérente à la mobilité latérale des cours d'eau, ce qui permet d'anticiper de futurs dégâts lorsque l'habitat est mal placé, généralement dans les concavités de méandres libres ou faiblement encaissés. (*iv*) Sur les grosses rivières, l'analyse géomorphologique a démontré également la pertinence de distinguer la bande active de tressage des terrasses alluviales afin de mieux évaluer les risques associés dans le fond de vallée. (*v*) Dans de nombreux bassins versants, les chenaux de rivière souffrent d'un manque d'espace lors de leur traversée de zones urbaines souvent densément peuplées. Face à cela, les solutions (hydrauliques) sont à présent limitées en ce qui concerne la reconsidération de la largeur du chenal, généralement insuffisante lors des crues, aboutissant à la reconstruction à l'identique des bords de ravine. Des solutions de bon sens existent pourtant pour éviter ou atténuer des inondations fluviales ou pluviales qui seraient provoquées par des aménagements mal conçus. (*vi*) Sur les rivières, s'il advenait que des solutions soient cherchées pour améliorer l'existant, il faudrait se tourner vers une réflexion globale pour redéfinir et intégrer la dynamique de « l'espace rivière » face aux « enjeux » qu'il est essentiel de hiérarchiser (qu'est-ce que l'on veut défendre en priorité contre les crues). La cartographie de l'espace de bon fonctionnement (EBF) serait une solution à envisager (au moins à tester) pour une meilleure intégration des principales fonctions (géomorphologie, hydrogéologie, hydrologie, hydraulique, biologie, biogéochimie) de la rivière et des pressions et usages anthropiques. (*vii*) L'atténuation du risque inondation face aux crues brutales passe pour beaucoup par la réduction de la vulnérabilité en agissant sur les enjeux. (*viii*) Les Réunionnais doivent se préparer à passer d'une adaptation pluriséculaire à la spécificité climatique (pluies intenses, réponse hydrologique rapide, très grosse variabilité intra-annuelle et interannuelle à l'échelle de l'île) à l'adaptation au changement climatique, qui se traduit déjà par une saison humide écourtée, donc une concentration des pluies plus forte, qui deviennent plus intenses. (*ix*) Ces constats hydro-géomorphologiques dressés précédemment rejoignent pleinement les perspectives de la DEAL, un service déconcentré de l'État français et organe essentiel de la gestion du risque inondation sur l'île de La Réunion. Face aux limites des protections strictement structurelles, qui peuvent engendrer un sentiment de fausse sécurité chez les riverains, la DEAL préconise de dépasser la logique d'endiguement pour s'orienter vers une stratégie globale de résilience territoriale, basée sur quatre leviers fondamentaux : l'anticipation et l'amélioration des connaissances ; la réduction de la vulnérabilité ; la gestion et l'adaptation aux crises ; l'acculturation et la culture du risque.

En conclusion, l'article souligne l'importance cruciale d'une gestion intégrée et proactive du risque inondation à La Réunion, face à des événements hydrométéorologiques de plus en plus intenses et fréquents. Bien que des mesures d'atténuation de l'aléa puissent être mises en œuvre, la réduction de la vulnérabilité est essentielle. L'analyse hydro-géomorphologique, couplée à une compréhension des dynamiques temporelles et spatiales du risque, est indispensable pour établir des stratégies efficaces. Il est impératif de reconsidérer les infrastructures existantes, notamment les digues, dont la conception ne prend souvent pas en compte le ruissellement pluvial, aggravant les inondations. Enfin, l'implication et la sensibilisation des communautés locales à la gestion des risques sont cruciales pour une action collective efficace.