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Roxana Popescu [1,2,3,*], Hélène Beraud [3] and Bruno Barroca [3]

1 Faculty of Architecture and Urbanism, University of Mons, 7000 Mons, Belgium
2 UMR 241 EIO, University of French Polynesia, 98702 Faa'a, Tahiti, French Polynesia
3 Lab'Urba Laboratory, Gustave Eiffel University, 77454 Champs-sur-Marne, France; helene.beraud@u-pem.fr (H.B.); bruno.barroca@u-pem.fr (B.B.)
* Correspondence: roxana-mihaela.popescu@u-pem.fr; Tel.: +33-07-6708-1259

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Abstract: Due to their sometimes devastating and, at the same time, transformative effects, the impacts of major hurricanes on small islands leave their mark both on the way territories operate and on their future development. This was the case during the passage of hurricane Irma over the island of Saint Martin in 2017. By analyzing the stocks and circulation of hurricane waste flows, our aim was to see whether the inherent evolution of Saint Martin's metabolism as a result of the island's total destruction tended toward a lasting transformation of its waste management system and, therefore, toward the territory's sustainability. This evolution was analyzed in a diachronic approach and over a short time frame. It was based on three structuring territorial metabolism dimensions: the intensity of waste flows, the spatial structure of the metabolism and the actors and techniques that explain it. Results show that while the intensity of the waste flows changed durably after Irma, the lasting transformation of the spatial structure and the actor system was less obvious and depended on the waste stream. Results also reveal the importance of reflecting on the development of recycling and reuse methods as a solution for improving post-hurricane waste planning on islands.

Keywords: hurricane Irma; territorial metabolism; island waste management; post-disaster stock and flow evolution

1. Introduction

This article focuses on post-hurricane waste management in island areas and, more particularly, revisits the hurricane Irma experience on the French part of the island of Saint Martin (in the West Indies) in September 2017. Twelve years after Hurricane Katrina, which devastated New Orleans in 2005, 2017 was an intense year, with ten consecutive hurricanes in the North Atlantic: Franklin, Gert, Harvey, Irma, José, Katia, Lee, Maria, Nate, and Ophelia. A few days before Irma, hurricane Harvey caused considerable damage in Texas and Houston, mainly due to very heavy rain. Following Harvey, Irma hit the West Indies, particularly affecting the islands of Saint Martin and Saint-Barthelemy (followed by Cuba and Florida). Irma stood out for the truly exceptional speed of its high winds, that lasted for over 24 h and which were estimated by the National Hurricane Center (NHC) at 155 kt (287 km/h) at the time of its passage over Saint-Barthelemy and Saint Martin. There were even short gusts estimated at speeds above 350 km/h [1]. As for the rain, which was not as heavy as for Hurricane Harvey in Texas, it "exceeded 150 mm in 6 h, while an excessively surge of 2.04 m was recorded in Marigot" [2]. At the end of September, Maria, also a category 5 hurricane, passed close to Guadeloupe and Martinique but it mainly affected Dominica and Puerto Rico [3]. Although Maria did not directly touch the islands hit by Irma, the swell generated at sea and the measures linked to the alert strongly disrupted the rescue operations, the solidarity between islands and emergency repairs on buildings

(tarpaulins for damaged roofs) and infrastructures. According to the Swiss Re reinsurance company, these three hurricanes—Harvey, Irma, and Maria—caused damages amounting to almost 93 billion dollars on insured property, and the total costs including uninsured property remained significantly higher. An estimate of Harvey's cost just for the Houston region was calculated at almost 200 billion dollars [4]. As far as Irma was concerned, according to the Central Reinsurance Fund, the damage insured under the natural disaster regime exceeded 2 billion euros on the French islands.

More than a third of the cost of recovery [5] relates to disaster waste management. Feedback shows that storms and hurricanes are hazards that generate particularly large amounts of waste [5–7]. Poor management disrupts the progress of emergency services and the restoration of technical networks (water, energy, etc.) and may even cause environmental damage (pollution), health risks (mosquitoes and pests, and open waste-burning), social damage (the pace and choice of areas to be cleared), economic damage (relaunching activities) as well as a deterioration in the image of tourist areas [8–11]. Feedback and the literature show all the difficulties of disaster waste management combining territories and hazards. These difficulties seem to be linked to several phenomena: insufficient waste facility, the need to avoid saturating the capacities of existing waste management systems, the impossibility of projecting one's self in terms of quantity and quality into the nature of the volume of waste. Beraud et al. [9] exposed the specificities of island environments in terms of waste management (availability of land, difficult access to other territories, low diversity of processing and upgrading systems), which make hurricane waste management particularly difficult.

This insular context, as well as the succession of hurricanes that hit structures that were already fragile and disrupted trade between islands, revealed all the difficulties in Saint Martin's waste management system. Setting up, in the middle of the emergency waste storage areas, illegal dumping practices and open-air waste-burning, and the difficulty in treating waste by conventional streams illustrated, on the one hand, the difficulty in managing the exceptional waste flows caused by the hurricane and also revealed, on the other hand, pre-existing weaknesses in the technical system. Beyond resistance and adaptation, the notion of resilience allows us to approach the "crisis" as a time that shows the weaknesses and the strengths of territorial systems in the face of hazard. The post-crisis period is, therefore, a suitable moment for making these systems evolve positively in light of the experience obtained from the crisis [12]. In Saint Martin, the weaknesses of the technical waste management system that appeared during the 2017 hurricane season go beyond the context of hurricane waste and reveal the dysfunctions that had already appeared in waste management during normal times.

In this article, we are concentrating on the transformations which were initiated during the post-disaster time, and which affect waste management. Our hypothesis is as follows: the experience of the 2017 hurricane season, and in particular of Irma, has had a lasting impact on the stocks and circulation of waste flows in Saint Martin.

In order to study this hypothesis, the first part of the article presents the specifics of waste management in Saint Martin from the point of view of its political organization (Section 2.1), waste production (Section 2.2) and the organization of the technical waste management system (Section 2.3). The second part focuses on the methodological framework proposed for studying the validity of the hypothesis specified above. If the mobilization of methods resulting from the territorial metabolism makes it possible to partially meet expectations (Section 3.1), the specificities of post-hurricane waste management as well as the specificities of the island territory force us to improve the standard methods (Section 3.2). Finally, the fourth part characterizes the transformation of the waste-management metabolism by showing up temporal and spatial variables.

2. The Specifics of Saint Martin's Waste Management Organization during Normal Periods

2.1. The Complexity of the Political Organization

Saint Martin is an island located to the north of the West Indies arc, which has been shared between France and the Netherlands since 1648 (the Mount Concorde Treaty). The French part of the island,

covering an area of 93 km^2, was administratively attached to the "department" of Guadeloupe from 1947 to 2007. Since 2007, it has had the status of an overseas territory governed by Article 74 of the French Constitution, that is to say, an Outermost Region of the European Union. The Dutch part, Sint Maarten, covers an area of 34 km^2, and is located to the south of the island. It has been an autonomous state dependent on the Netherlands since 2010 and possesses the status of an Overseas Country and Territory of the European Union. Sint Maarten is therefore located outside the EU. The different political affiliation of these two territories has given rise to two separate waste management systems, each with its own administrative constraints. While the French part is subject to European regulations, they do not apply to the Dutch part, which is not part of the European Union. Despite these differences in status, there is no border control between the two parts of the island, which facilitates the free movement of goods but also of waste [13]. The rest of the article is only concerned with the waste management system on the French part of the island. Relations with the Dutch side most certainly influence how the system works but they are unofficial and will not be taken into account in this analysis.

The specific nature of the development and evolution of Saint Martin's waste management system is therefore intrinsically linked to this political organization. Saint Martin is characterized by a dual insularity, both in relation to metropolitan France and to its status as a municipality belonging to Guadeloupe. This geographic distance was reflected by a certain slowness in developing the technical infrastructures required for efficiently collecting and treating the volume of waste at the same speed as that at which the territory has been developing. Until 2007, the municipality of Saint Martin was financially dependent on Guadeloupe, which also had difficulties in acquiring waste treatment infrastructures of a sufficiently high standard and in structuring waste valorization supply chains [14]. Despite certain efforts, informality was very much present there. The landfill operated by the municipality since 1991 was not up to standard and was only equipped with a small composting unit. The recycling unit inaugurated in 2006 did not yet have its administrative permits. The selective collection of packaging waste was already in place, and a private recycling center treated a small part of the recyclable materials, the rest being shipped to Guadeloupe or metropolitan France. The community was also faced with a problem of illegal dumping.

The municipality's change of status to an overseas collectivity, due to the organic law of 21 February 2007, gave Saint Martin more autonomy to exercise all the powers devolved to the municipality, the "department" and the region, as well as those transferred to it by the Government. This means that the environmental code, which regulates waste management in French territories, will continue to be applied, but the collectivity has the possibility to adapt it to the specificities of its territory, after the government's approval. Despite its remoteness from the continent, some eco-organizations also have the obligation to pick up recyclable waste through public procurement contracts put in place by local authorities. Since its autonomy, the collectivity has been responsible for collecting and treating non-hazardous waste. It now develops its own strategy and decides independently on the investments required. Environmental jurisdiction, including the management of hazardous waste, remains, however, the State's prerogative and is handled by the Department of the Environment, Planning and Housing based in Guadeloupe.

This change in the collectivity's status has enabled it to master all the competences concerning waste (from management to strategic planning). Since 2007, the island has experienced an increase in the structure of its collection streams, made possible by the development of collection and processing infrastructures. Concerning collection, voluntary drop-off points for recyclable waste (two 180-L bins, three 770-L bins and, for plastic waste, 43 voluntary drop-off points, forty-one 180-L bins and twenty-two 770-L bins) and the Galisbay Bienvenue collection site have been created [15]. For treatment, a waste-sorting and recycling site called the Grandes Cayes Ecosite has been created, and the landfill for burying household and similar refuse operated by the municipality has been brought up to standard. In compliance with French regulations, the site was classified as a Non-Hazardous Waste Landfill (for household refuse and similar). Waste collection was delegated to local private operators in the

context of public procurement procedures. The ecosite operation and the landfill were delegated to the company Verde SXM in 2011.

2.2. Weight of the Tourism Sector Influencing Waste Production and Management

Waste production and management on the island of Saint Martin is closely related to changes in the island's demographic and socio-economic characteristics.

Based in the past on exploiting the salt marshes and cultivating tobacco and then cotton and sugar cane, Saint Martin's current economy is largely tertiary and dependent on tourism, which has grown significantly since the 1980s, driven by the dynamics of the Dutch side and by the opportunities generated by tax exemption systems in 1986. The tourist boom of the 1980s has largely influenced the population's demographic evolution. As a result, the 1980–1990 period was marked by a significant increase in the population, going up from 8000 inhabitants to 28,500 inhabitants. This increase was mainly due to the migratory balance. Migration, which originated largely in Haiti and the Dominican Republic, can be explained by the need for labor in construction and tourism activities. In 2015, Saint Martin had a population of 35,684 inhabitants [16].

Today, the island's activities are concentrated on non-market services and other commercial interests, which respectively account for 6.4% and 33.9% of the total employment. Accommodation and catering and the construction business also benefit from Saint Martin's tourist attractiveness and respectively account for 26.1% and 6.6% of total employment [16].

The tourism sector is, therefore, an important source of waste production, due to related activities, which generate waste themselves (catering, accommodation, and construction), but also to the waste generated directly by tourists. In the context of Saint Martin, it is difficult to separate the different sources. According to data recorded by the Verde SXM company at the entrance to the landfill, the variation in the production of residual household waste over a year is influenced by the drop in the tourist season during the June–September period [17]. In addition, due to its free-port status, which does not oblige port authorities to monitor imports, it is difficult to quantify the volume of waste on the territory.

Although tourism is the pillar of Saint Martin's economy, the French side does not have port and airport infrastructures suitable for handling the mass tourism that benefits the Dutch side, which captures almost all the cruise business. The number of cruise passengers arriving in Marigot, in the French sector, remains extremely low. They do not contribute much to the waste produced directly by tourists. It is more small-scale tourism, where visitors remain longer, which contributes to waste production and calls on local waste collection infrastructures. In this respect, the highest level of tourist frequentation on the French side was reached in 2014, with nearly 594,000 tourists welcomed to Saint Martin and 2,106,000 cruise passengers arriving in transit from the Dutch side. It should be mentioned that tourists coming on a cruise only stay a very short time on the island (one day on average) and are therefore not likely to contribute significantly to waste production. In 2016, 109,979 passengers arrived at Grande Case airport and over 333,000 nights' accommodation were sold. Leisure sailing is also part of the tourist landscape of the island of Saint Martin, which is a popular port of call for navigators with a capacity of around 750 places [16].

The main source of waste generation continues to be the residential population. All finished products on the Saint Martin market are imported, which also generates additional waste due to the packaging required for transporting these products by sea or air. For the year 2015, the Verde SXM company declared that it had buried 18,463 tons of waste generated by the population and 1855 tons of waste generated by professionals, therefore a total of 20,318 tons [17].

A sorting culture is also struggling to find its place on the island. Multiculturalism, which is a specificity of Saint Martin in the Caribbean, was often invoked during the field research by public authorities, associations and residents as being a reason for the difficulties in setting up a sorting system: different socio-economic levels between the communities present on the island, communications in French when not all members of the different communities speak French, different waste management cultures, not enough awareness and educational campaigns adapted to the local specificities, etc.

Selective collection is relatively ineffective. Only an extremely low proportion is sorted and sent to recycling streams. Following a study on the characteristics of the waste present in an underground storage compartment at the Grandes Cayes landfill, carried out in 2018, on a volume of recyclable waste that had undergone selective collection, and estimated at 5370 tons, 5100 tons ended up by being buried. Only 4% of non-glass packaging and 9% of glass packaging [18] was sorted.

2.3. Organization of the Waste Management Service: Streams and Facilities

Waste collection in Saint Martin is organized in four streams: household waste, bulky waste, green waste and selective sorting at voluntary drop-off points. There are several operators for collecting each stream who carry out the same type of collection but on eight different sectors of the island, decided by the local authorities More precisely, there are 12 operators divided into eight collection sectors for household waste and seven collection sectors for bulky waste (which also includes green waste): five operators for collecting household waste, four operators for collecting bulky items, two operators for collecting green waste and one contractor for collecting sorted waste. As can be observed in Figure 1 (below), the organization of the waste collection in 15 areas that overlap and performed by 12 private operators is a local specificity. Moreover, as can be noticed, there are areas where there is no collection of bulky waste, the inhabitants having to transport the waste themselves to the voluntary drop-off points. These voluntary drop-off points are not represented in Figure 1. The collection takes place from 6 p.m. to 6 a.m. Transporters need to make three or four return trips to the landfill to deliver all the waste.

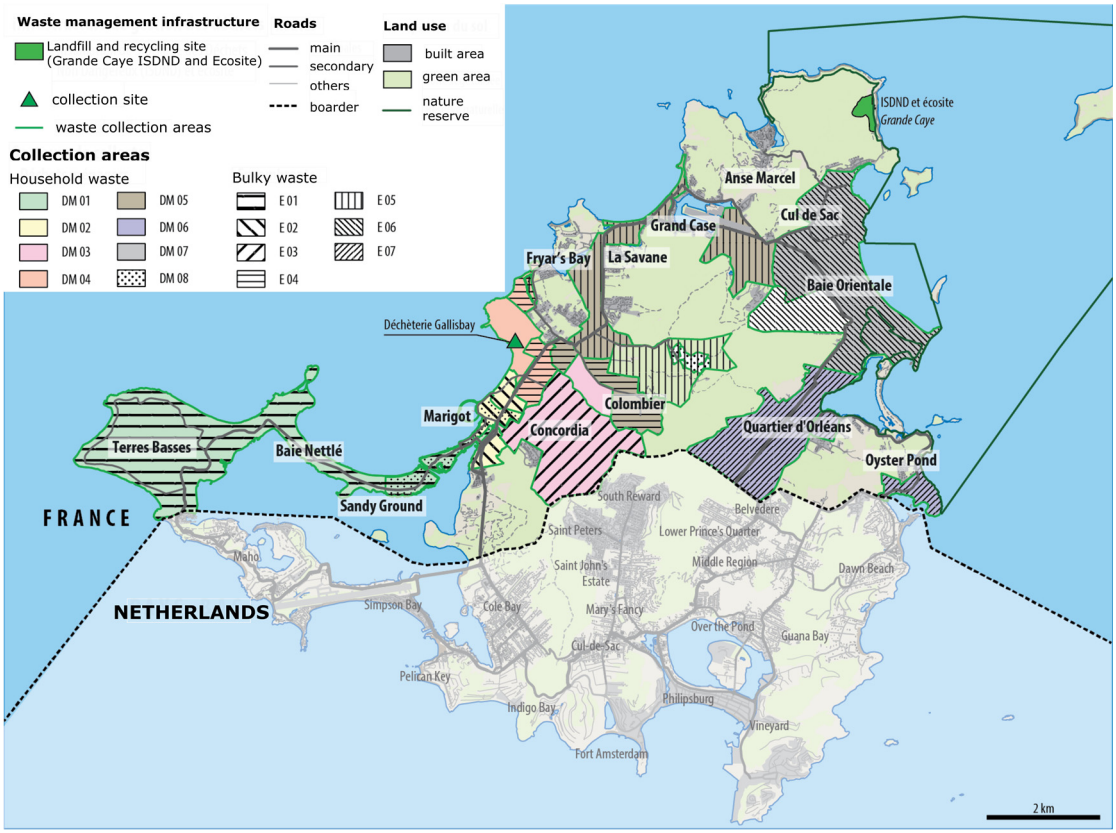

Figure 1. Waste management infrastructure and waste collection areas in Saint Martin (Source: Collectivity of Saint Martin, produced by DéPOs project 2020).

An ELV (End-of-Life Vehicle) treatment center was opened in Grandes Cayes in 2015. It enables vehicle carcasses from the French part of Saint Martin to be decontaminated with the help of a hydrocarbon separator. Since 2013 a treatment unit has also existed for processing infectious risk healthcare waste

(DASRI). It is managed by a private company that offers treatment, disinfestation, and shredding. A special vehicle is used for collecting waste from producers: clinics, hospitals, the collectivity of Saint Martin, laboratories, doctors, nurses, midwives, dentists, veterinarians, undertakers and self-treatment patients.

Waste streams (apart from the DASRI) are centralized at the Grande Cayes site, which has become the only facility for waste: household waste collected by private operators (household waste, organic waste, bulky waste, WEEE), waste arriving from the collection and separation site (Galisbay), waste from voluntary drop-off points for collecting household packaging waste, waste from economic operators and waste from general island cleaning campaigns organized by the collectivity at least once a year, plus the ELVs which are systematically collected. On the Grandes Cayes site, waste from the island is either buried, processed and sold locally, redirected to valorization supply chains with eco-organizations or sold on the waste market. In 2013, initial first contracts with eco-organizations were also signed for Waste Electrical and Electronic Equipment (OCA3E eco-organization,) and household packaging (Eco-Emballages). Table 1 shows the different types of waste and their treatment for the year 2015.

Table 1. Waste streams and treatment methods (Source: Verde SXM, Produced by DéPOs Project 2019).

Waste Streams	On-Site Treatment	Destination	Eco-Organization
Green waste	Crushed and mixed with sludge from the collectivity's treatment plant on the composting platform	Sale of compost to NF-U 44-095 standards (from 2014)	NA
Glass	Crushed	Sand and glass gravel are marketed on the island under the name "SWALIGLASS" Marketed to companies on the island for filling electricity supply trenches Used internally on the site for making concrete structures or for route cleanliness	NA
WEEE	Massification Grinding	AER in Guadeloupe International scrap markets	Ecologic
Furniture	Massification		VALDELIA
Ferrous and non-ferrous metal waste	Massification, sorting and compacting	Shipped to international markets after processing in specialized scrap installations in Europe	NA
Cardboard boxes resulting from business activities	Sorted, compacted, and dispatched for upgrading		NA
Packaging waste	Massification	Sorted and upgraded at ECODEC in Guadeloupe	ECODEC EcoEmballages
Batteries and accumulators	Massification		SCRELEC
Bulbs	Massification		Recylum
Used engine oil	Recovered from garages free-of-charge by a service-provider	Upgraded at OSILUB (Rouen) under the terms of an ADEME contract	NA
Cable	Massification	Dispatched to Recyclables for upgrading copper and aluminum	NA
ELV	Storage, decontamination, and dismantling		NA
Rubble	Crushing, sorting	Reuse on site for site design and landfilling	NA

The start-up of these systems as early as 2013 has transformed the circulation of waste flows and increased the volumes of waste leaving the territory. The Verde SXM company noted that there is a need

to improve sorting performance by optimizing the sorting platform and by raising awareness among the population and professionals on sorting practices. In 2015, the buried part of waste delivered to the site represented 85% and the recycled part, down on 2014, amounted to 15% [17].

This operation reflects weaknesses which were already summarized by the Saint Martin public authorities in 2014: regulatory difficulties (the obligation to treat waste locally or to export it to Guadeloupe and then to Europe), a market that was not sufficiently developed, a small geographical area available, an overloaded landfill, the absence or the low number of collection and treatment systems for hazardous waste, the low level of recycling, the persistence of illegal dumping. It appears difficult to install effective treatment systems because of the limits induced by the size of the territory and the lack of land [19,20].

Therefore, it is clear that the technical waste management system had already encountered a number of difficulties before hurricane Irma hit, largely due to its insularity, its economics and its political organization. As disasters tend to exacerbate the difficulties felt in normal periods, we wanted to study the impact of this type of phenomenon on the technical waste management system. By relying on the conceptual framework of territorial metabolism, we shall analyze the transformations desired or undergone by the technical waste management system by looking into the waste stocks and waste flow circulation after the passage of hurricane Irma.

3. The Method

3.1. General Methodological Framework

For the past twenty years, work on the island's metabolism has been carried out in the perimeter of socio-ecological studies promoted by the Institute of Social Ecology of Vienna or by industrial ecology [21]. These two fields of research consider the territory as being an interface between society and the biosphere. Territorial metabolism accounts for this interface by representing the territory as a set of stocks and flows of materials and energies circulating within it. In addition to the accounting dimension of flows and stocks, it also covers the description and understanding of the natural and social processes which are at the origin of the circulation of these streams and their evolution, and this in order to modify or transform the territorial metabolism [22,23]. The goals of social ecology and industrial ecology differ somewhat. In simplified terms, where social ecology approaches attempt to include and understand the trajectories of territorial systems and to study and contribute to their socio-ecological transition [24–26], industrial ecology directs its reflexions more toward the knowledge of the streams of current materials for dematerializing or decoupling economic growth and the consumption of materials through symbiosis approaches and work on analyzing life cycles, for example [27]. However, both approaches reflect on the means of improving a territory's sustainability.

Insular territories, in particular, lend themselves to this type of work because the question of their sustainability is paramount. In general, their isolation, their frequently limited size and, consequently, the pressure and conflicts on the subject of land resources, the availability of natural or water resources and their economy, which is often dependent on external factors (tourist activities, agriculture, mineral extraction, etc.), make island territories particularly vulnerable to local and global economic, environmental and social changes [28,29]. Furthermore, such territories have the particularity of having geographic borders that often coincide with administrative borders, which, as such, makes it easier to work on the interactions between societies and the natural environment [21].

In their article, Petridis et al. show the diversity of the work undertaken in the field of industrial ecology and social ecology [21]. It would appear that these works model the flows of materials and energies in order to propose recommendations for a more sustainable management of insular resources, and that others propose to explore the dynamics of socio-ecological transition to measure their consequences on the viability of the territories under study. More specifically, on the subject of waste, the article of Eckelman et al. [29] shows that, if analysis methods of territorial metabolisms are mobilized for defining the volume of waste produced on insular territories together with the circulation of these waste flows,

the finality is often an improvement in waste management by reflecting on the development of re-cycling or re-use supply chains or by the use of territorial planning works.

Our work moves along these lines by using territorial metabolism as a conceptual basis. As such, it relates to an insular territory and its waste stocks and flows. Nevertheless, it has the particularity of studying the island in question after the passage of hurricane Irma, after which the island was significantly affected by the production of hurricane waste.

3.2. Specific Methodological Framework

Studies concerning the experience of territories hit by large-scale disasters show that the quantity of waste produced following the damages to buildings, infrastructures and the natural environment can be very significant and diverse [11]. Therefore, looking at the possible evolution of metabolism following hurricane Irma in Saint Martin requires a quantitative approach to waste stocks and flows. In this respect, the analysis can be similar to those already carried out under normal circumstances. Nevertheless, our knowledge of managing this type of phenomenon indicates (1) that these quantities of new waste potentially modify the circulation of waste flows in both time and space over relatively different time periods, and (2) that any such modification is likely to be different depending on the type of waste and on the period during which waste pre-collection occurs (during the immediate post-crisis period, a few months later, or even a few years later).

Works on the evolution of a territory's metabolism have been carried out over more or less long periods in order to study the conditions for implementing a socio-ecological trajectory in continental territories [30–33] or in island territories [34,35], for example. However, these publications do not include studies on the circulation of material flows in shorter time scales. Only three research works have been identified as studying the relationship between a disaster and the development of metabolism: Symmes et al. [36] study the consequences of a natural disaster (a cyclone and a rise in sea level) on building materials present on the Island of Grenada; Quinn [37] analyzes the impact of post-Katrina reconstruction on the New Orleans' metabolism; and Wildenberg and Singh [38] study the consequences of the 2005 tsunami and reconstruction on the socio-ecological system of the island of Kamorta, in the Nicobar archipelago. However, these works do not specifically concern disaster waste management. In this respect, the present article makes a more detailed contribution to the field of island metabolism by working on a disruptive episode over particularly short lapses of time.

To identify the characteristics of the metabolism that we are studying, we will be relying on the three structuring dimensions of territorial metabolism as they were defined by Kampelmann and De Muynck [39]. Therefore, our analysis will focus on the intensity of the metabolism, i.e., the quantities of waste produced and put into circulation. This intensity will be studied in terms of waste flows in order to reveal the effects of the existence (or absence) of waste management streams; the spatial structure of the metabolism, i.e., the spatial organization of waste flows circulation and the part of the metabolism that is internalized or externalized in the system, as well as the actors and techniques that organize waste flow circulation. In this last case, we highlight the roles played by the different actors and all the technical conditions that explain and condition the metabolism. In addition, as previously mentioned, these three driving forces are analyzed in a diachronic approach, so as to take into account the temporal evolutions inherent in post-disaster waste management.

3.3. Data-Collection Method

Data concerning the development of waste-flows circulation on the territory of Saint Martin after the passage of hurricane Irma, in 2017, were collected at the time of two missions carried out in May 2018 [40] and May–June 2019 [41]. Sixty semi-structured interviews were carried out with public stakeholders in waste management, crisis management and regional planning, with building and public works contractors who worked on post-Irma waste management and with private actors in waste management, public services and associations for the protection of the environment (14 interviews in 2018 and 46 interviews in 2019). These interviews were supplemented by discussions

with the population in the context of formalized questionnaires (63 inhabitants questioned in 2019) or of semi-structured interviews (16 inhabitants questioned in 2018). These interviews were complemented by a field observation work in order to locate any illegal post-Irma waste-dumping sites and any potential stocks of reconstruction waste that had not yet been collected (abandoned houses damaged by the cyclone).

These discussions and observations enabled quantitative information to be collected on the production of post-Irma waste by assessing the waste arriving at the Grandes Cayes ecosite (the main waste facility for normal waste at Saint Martin). This quantitative data is incomplete and vague, imperfections inherent to disaster waste. This can be explained in several ways: the collection of information on disaster waste is not standardized in post-disaster return on experience, new actors intervene who are not identified as being concerned by waste problems, informal management methods exist, waste is disseminated over time and space, and waste management has been carried out in an emergency situation, which means that part of the volume is not captured by conventional waste management streams, and is therefore not monitored.

In order to reduce these inaccuracies, this quantitative information was supplemented by extra details concerning the organization of waste flow management in the weeks and months following hurricane Irma. These interviews enabled us to increase our knowledge of the volume of waste produced both from quantitative and qualitative points of view, our understanding of the different changes in the organization of waste flow circulation over the territory depending on the post-disaster period and our understanding of post-Irma waste transfer operations deferred over time, as they depended on the date of return of residents who only stay part-time on the island. This phenomenon was also observed in France after storm Xynthia's passage over the Vendée coast in 2010 [42].

4. The Study of the Evolution of Saint Martin's Insular Metabolism after the Passage of Hurricane Irma Applied to Waste Management

The passage of a hurricane generates large quantities of waste. Vegetation, goods, equipment, constructions, cars, etc., are blown away, damaged by the wind or soaked by rain, and, as a result, become waste or debris. However, the moment when this waste is brought to public storage areas varies depending on the time taken for restarting the territory, the urgency with which certain strategic roads and residential areas are cleared (putrescible waste, furniture waste, WEEE and construction waste, for example), the type of damage to businesses or buildings, compensation for disaster victims, etc. The variable production of waste over time is described in the literature as having three phases [8,10,43]. A first, urgent phase, during which roads are cleared in order to provide first aid and to enable vital technical networks to be repaired. During the second, cleaning phase, most waste is collected and treated, and demolition work begins. The largest volume of waste is collected during this period. A third, much longer phase then follows. This is the deconstruction/reconstruction phase (giving rise to construction waste) and the repair phase of infrastructure used for handling post-disaster waste. As shown is Figure 2, the post-hurricane waste flows in Saint Martin also followed these phases, from the moment when the hurricane impacted the island until the territory returned to its normal functioning. The delimitation in time of these phases, as presented in the figure below, is established by the local public authorities. However, the intensity of the waste flows, as will be explained in the following section, shows a different temporal dynamic, that questions whether the waste management public policies are adapted to the needs.

It can be seen that, in these different phases, Saint Martin's territorial metabolism changed in terms of intensity, the spatial organization of its waste flow circulation and the actors who were mobilized.

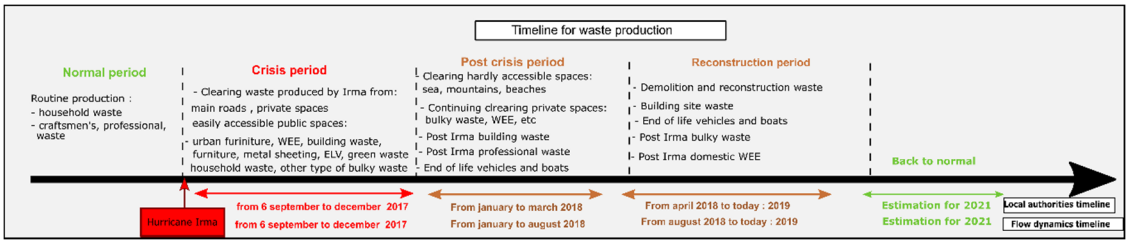

Figure 2. Timeline for the production of waste in Saint Martin following the passage of hurricane Irma (Produced by: DéPOs Project 2019).

4.1. The Intensity of Waste Flows Was Modified in the Long Term after Irma

As has been seen on many other territories [4,8,11], the volumes of waste produced by hurricanes are enormous. On the basis of the discussions held in the field 6 and 18 months after Irma, we were able to highlight this type of increase in waste production [40,41]. Thus, between 7 September 2017 and 30 June 2018, the Grandes Cayes ecosite received 55,889 tons of post-Irma waste. In fact, this waste only represented part of all the waste generated by Irma. According to the director of the Grandes Cayes ecosite, Irma generated the equivalent of two and a half years' production of normal waste, and the equivalent of five years' production of end-of-life vehicles [44]. During the phase of transporting waste from temporary storage sites to the landfill at Grandes Cayes, nearly 300 to 400 trucks entered the ecosite every day, instead of the usual 70 trucks per day. Two years later, the flow of lorries was still higher than normal: approximately 170 trucks per day [44]. The stream of bulky items arriving at the landfill is still three times higher than in normal periods, and reconstruction waste continues to arrive in very large quantities [41].

This significant increase can be seen through the evolution in the quantities of waste treated at the Grandes Cayes site since 2015. Table 2 shows that the volume of waste treated on the site has doubled between 2017 and 2018.

Table 2. Evolution in waste treated by the Grandes Cayes Ecosite (Source: Verde SXM and IREP [45]; Produced by DéPOs—2019).

Year	2015	2016	2017	2018
Quantity of waste treated at Grande Caye Ecosite	34,155 tonnes (Source: Verde) 33,307 tonnes (Source: IREP)	42,311 tonnes (Source: IREP)	83,760 tonnes (Source: IREP)	67,184 tonnes (Source: Verde)

Figure 3, on the other hand, shows the evolution of four specific waste flows from 2017, following the year of hurricane Irma, up to 2019.

The bulky waste is the flow with the most significant increase in variation, encompassing WEEE, furniture and all kinds of goods damaged by the hurricane. As a very limited separation of waste was done during the collection, temporary storage and transportation to the landfill, all these types of waste were included in this category by the Verde SXM company workers when registered at the entry of the landfill. The first peak corresponds to the intense clean-up process during the crisis period (September to December 2017), followed by a drop when the operations were officially over. The second peak shows that, in reality, not all the post-hurricane waste was collected during the crisis period and that waste continued to be produced. This phenomenon can be explained by different local factors, as clean-up actions done by the evacuated inhabitants that started to come back to the island and clean-up campaigns to collect the remaining waste from areas with difficult access. Two years after the hurricane, although stabilized, this flow is still higher than in the pre-Irma period.

Another type of waste flow whose production is still significant in the long term is the construction waste mainly related to current reconstruction operations. Hurricane Irma damaged 95% of the buildings on the island, 27% of which required rebuilding [46]. The production of this type of waste generally takes place at a different time to that of other types of disaster waste. During the crisis, its collection rate

dropped comparing to normal times. Indeed, except for metal sheets that were collected during the first months after the hurricane and that were classified as bulky waste, the rubble from buildings whose walls were destroyed, windows or doors, were collected later after the end of the clean-up operations. Once the demolition/reconstruction process begins, other construction waste is produced. To some extent, this depends on the compensation for damage provided to inhabitants by insurance companies, for activities which are insured, on disaster victims' financial resources and the availability of building firms and building materials, for example. Only 49% of the buildings had been rebuilt by August 2019 [47].

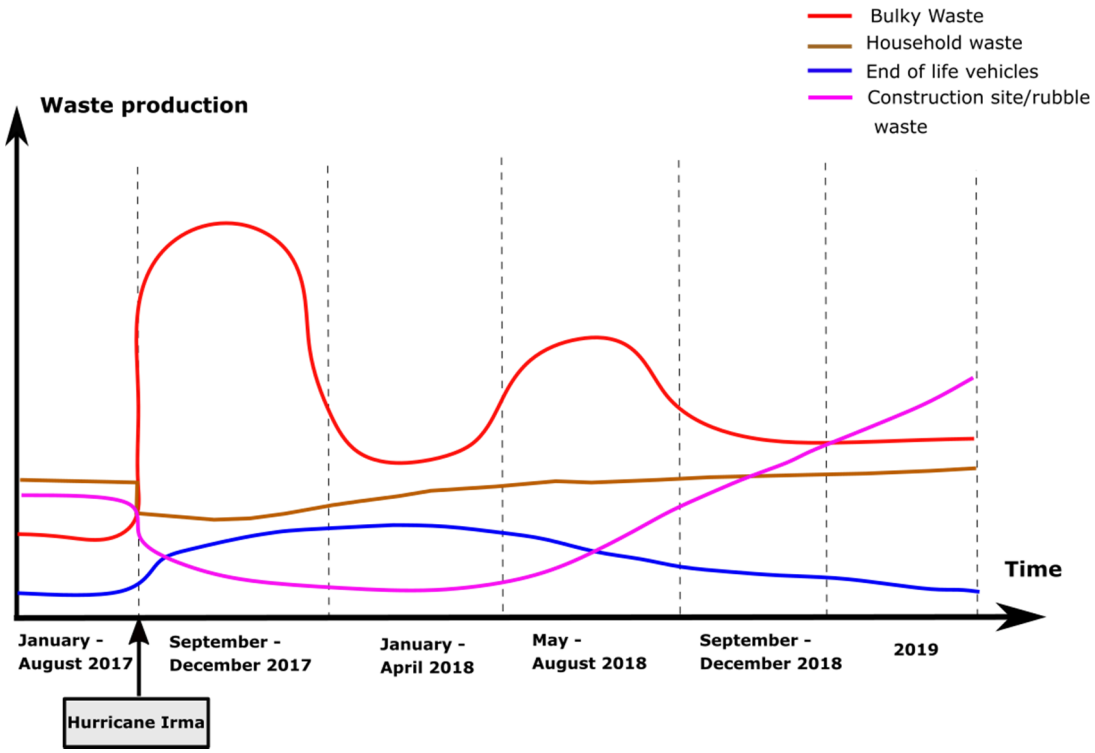

Figure 3. Evolution of waste flows after hurricane Irma in Saint Martin (Source: Verde SXM, field research, [2]) produced by DéPOs—2020).

The end-of-life vehicles were collected separately especially during the first year after Irma, thanks to a program financed by the government. The program took into consideration pre- and post-Irma cars as well. Although there are still abandoned vehicles to collect in public or private spaces, at present the volume is starting to decrease.

In addition to post-Irma waste, the evolution of the intensity of waste stocks and flows on Saint Martin's territory also depends on the so-called "normal" waste produced by the population and all the normal economic activities. Irma had important consequences on the way the island was run: the departure of many inhabitants and significantly reduced tourist activities, which used to be the island's principal source of income. F. Vinet et al. also show that the collection of household waste dropped by 20% during the post-Irma period [2]. Field interviews also confirmed this conclusion, showing that only 21% of the population used the official drop-off points in normal times to deposit their household waste, while others discharged it in the same drop-off areas for bulky waste or burned it.

4.2. Modification of the Spatial Structure of Waste Streams

The increase in waste production and the type of waste produced made the existing waste management system unsuitable for collecting and treating waste. Moreover, the technical waste management system itself was affected by the hurricane. A number of voluntary drop-off points, the basis for waste-collection under normal conditions, were damaged by Irma. The road leading to the Grandes Cayes Ecosite was

cut, and machines present on the site were destroyed. An ad hoc organization was set up in a few days, which we will re-discuss in Section 4.3 in order to take a closer look at its design. At this point, we are more concerned by the network's spatial reorganization.

In the first few days after Irma, cleaning operations were intense. At the time, the urgency was to clear the roads blocked by the unending mass of waste resulting from house-clearing. Eleven temporary storage sites were created on sports grounds, car parks and waste land [38] for quickly removing house-clearing waste from public roads. The collected waste was transported to the temporary storage sites while waiting to be transferred to the Grandes Cayes Ecosite. In this way, these sites were more specifically intended to stock waste while waiting for the access roads to the ecosite to be reopened. As we will see in Section 4.3, the organization set up by Saint Martin's local authorities and building and public works companies was assisted by another spontaneous, informal spatial organization (Figure 4): drop-off storage sites that were spontaneously created close to temporary storage sites along the main roads, and in out-of-the-way zones, mostly by the population. These temporary storage sites and drop-off storage sites for disaster waste supplemented the normal voluntary drop-off points for normal waste. The collection of this waste was not carried out using the same organization as for collecting normal waste. The initial delimitation of the new collection sectors was done spontaneously by the local building and public works companies depending on their geographical localization. These sectors are also areas where they have been operating for a long time. Therefore, they had a very good knowledge of the terrain. As can be observed by comparing Figures 1 and 4, new waste collection sectors were created and finally decided by the local authorities together with the building and public works companies in charge of waste collection, the priority being to re-establish the access to critical infrastructures (hospital, public institutions, petrol stations, etc.). Once the urgent phase was over, intensive cleaning of the island continued until the end of October, with a sustained and regular supply of waste commingled on temporary storage sites.

Between mid-November and the end of December 2017, the destocking phase gave birth to another very intense flow of trucks transporting waste from temporary storage sites to the Grandes Cayes Ecosite.

Gradually, the organization for post-Irma waste management implemented in the last quarter of 2017 was brought to a stop by the end of December 2017. The temporary storage sites were then closed in order to prevent any further dumping. This situation led to an increased demand in drop-off sites close to these sites, as there was no interruption in waste production [41]. Building reconstruction operations began in January 2018. Certain affected inhabitants, in particular the owners of holiday homes, were only just beginning their cleaning operations. Although part of the population continued to use the normal collection infrastructure that was now functioning, (voluntary drop-off points, Galisbay collection site, Grande Caye Ecosite), another part continued to use the drop-off sites, although this practice was discouraged and declared illegal. Moreover, small construction companies that did not want to pay the tax for construction waste disposal at the Grande Caye landfill also discharged their waste to these drop-off sites. Therefore (Figure 3), the number of informal drop-off sites increased significantly from that time onward (Figure 5). As the clean-up operations were officially over, in December 2017, and the waste collection system returned to its initial functioning, the drop-off storage sites were considered illegal dumping areas. Therefore, private operators were not obliged to collect them. We can observe on Figure 5 a certain dynamic of these illegal dumping areas. While in 2018 some drop-off sites disappeared as a result of exceptionally public procurement processes for waste collection, other sites appeared nearby in 2019. Although one of the most important criteria that explains this phenomenon is cost-related, when looking at the island's scale, these informal drop-off sites continued to play the role of the temporary storage sites put in place during the crisis period, by storing secondary disaster waste flows generated mostly by the reconstruction but without becoming permanent illegal dumps. Although the clean-up process is slow, the waste at these sites tends to be collected and transported to the Grande Caye landfill.

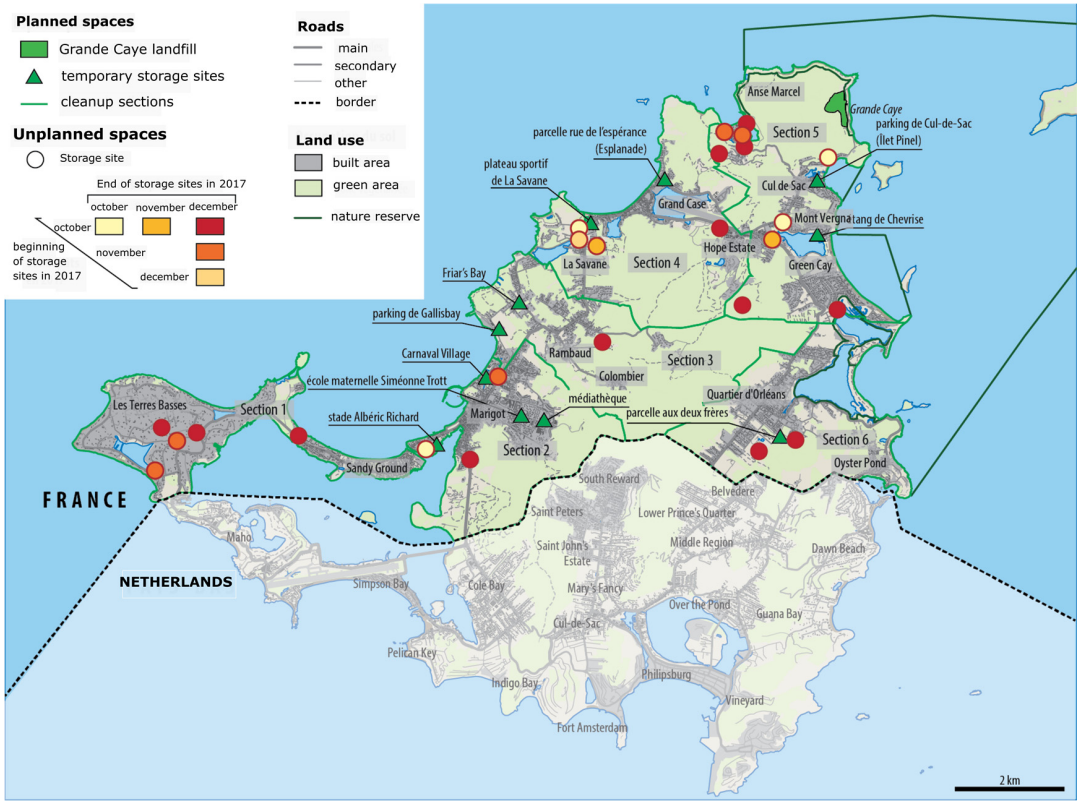

Figure 4. Spatial organization of post-Irma waste management in 2017: storage areas (Produced by: R. Popescu; DéPOs Project—2019).

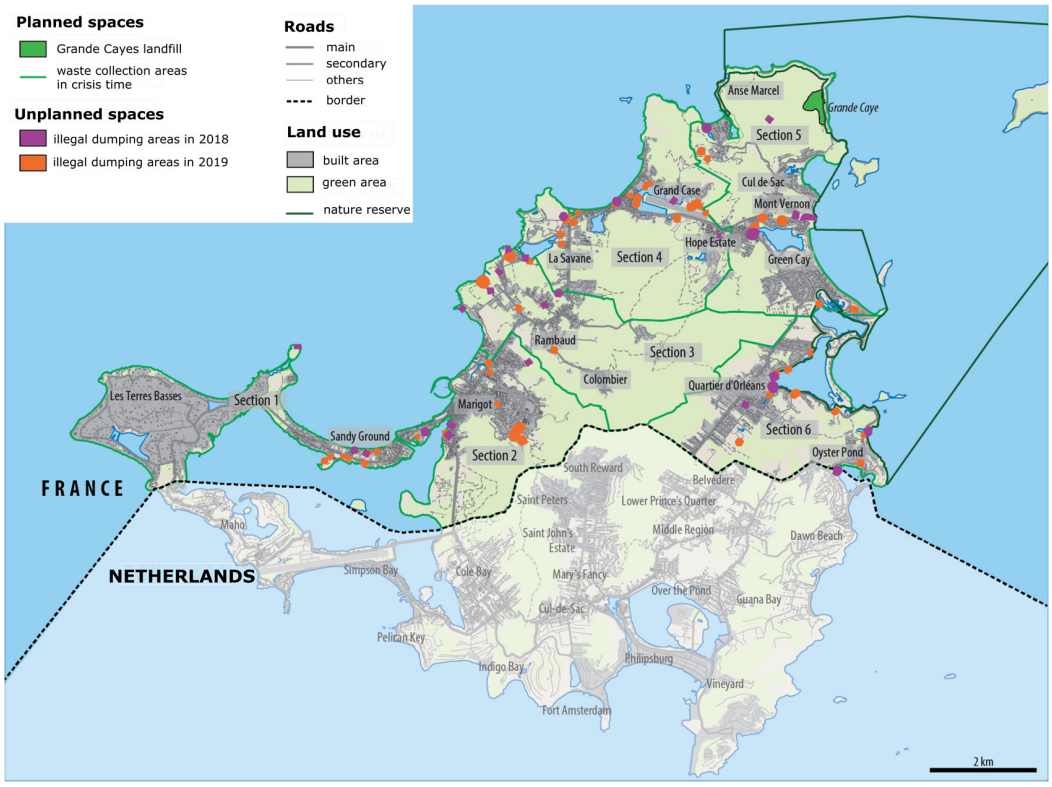

Figure 5. Spatial organization of post-Irma waste management after 2017: storage areas (Produced by: R. Popescu; DéPOs Project—2019).

Hence, the volume of waste produced by Irma, as well as the damage to collection and treatment resources, modified the circulation of waste flows, linked to the organization set up by the actors in waste and crisis management. Although, as we saw previously (Section 2.3), waste management was under the responsibility of Saint Martin's local authorities, which delegated waste collection to about ten different companies, new actors began to play a role after the passage of Irma.

4.3. Temporary Reorganization of Actors after Irma

Although no post-disaster waste management planning existed before Irma, and nothing in the post-disaster management plan (the ORSEC Plan) concerned disaster waste, it is interesting to note that the spontaneous organization which was set up on the day after the island was hit by Irma was the result of the know-how possessed by certain actors, inherited from Luis hurricane, which had hit the island hard in 1995. Certain construction contractors who were interviewed explained that the rapid intervention by companies in the building and public works sector and the creation of 11 temporary storage sites could be explained by vivid memories of this previous event [41].

As seen in other similar situations, the quantity and quality of waste produced does not allow normal waste collection actors to intervene in the collection of waste generated by a disaster, either because not all of their vehicles are suitable, or because they are not sufficiently equipped. Therefore, in the emergency period during the first week after Irma, it was first and foremost for technical reasons that participants were reorganized. Although the waste collection companies whose contracts were in force could have subcontracted to construction companies possessing appropriate equipment, post-crisis organization criteria were different. Building and public works companies played a crucial role in managing hurricane waste throughout the cleaning-up period. This can be explained for the most part by the important role played by building and public works companies in the past history of the island's development. As a result, a complex system of actors was set up—complex because it comprised public, private and civil society actors.

In the first days after Irma, building and public works companies worked alone in clearing up the main lines of communication and creating temporary storage sites. Subsequently, the "actor system" grew with the gradual spontaneous mobilization of additional resources (human, material and financial). The first players arriving from outside the island were companies in Guadeloupe's building and public works sector, mobilized by the "Société d'Economie Mixte de Saint Martin" (SEMSAMAR). Their mission was to take action on rented social housing on the island. The armed forces were also mobilized by the State in the framework of the ORSEC (Civil Security Response Organization) plan. For example, toward the end of September, the French Navy's Projection and Command Ship "Tonnerre" significantly increased the means of waste management thanks to its technical and human resources. They accelerated the clean-up speed and opened a new access route to the Grandes Cayes landfill. Subsequently, several small local companies were also created. They took part in the cleaning up process. As a result, the "actor system" reached its peak in terms of numbers during October, before starting to decrease.

October was also the most intense time for cleaning and transporting waste from drop-off storage sites to temporary storage sites. The new actors from the outside were perceived as a threat by local building and public works companies which wanted to monopolize the market for financial reasons. Once the access road to the landfill had been re-opened, temporary storage sites began to be destocked. The local building and public works companies wanted to regain control at this stage. The head of the risk management mission at the Saint Martin collectivity explained that around fifty companies from the local building and public works sector negotiated over-the-counter contracts with authorities for transporting waste stored on temporary storage sites to the Grandes Cayes landfill. The payment system was based on the number of rotations and not on the number of tonnes, which worked in favor of the building and public works companies. The overall cost of cleaning up the island was 15 million euros [41].

This new reorganization of the actor system was reflected by a visible drop in the level of cleanliness and the appearance of new drop-off sites on the island during the months of November and December

(Figure 4). This phenomenon can be explained in various ways: the departure of the armed forces, the end of funding for cleaning operations and the impossibility of continuing to pay the work forces, the attention paid by building and public works companies to the destocking phase rather than to cleaning the territory and the waste flows that continued to be generated by the population.

Therefore, at the end of the clean-up, after the last storage sites had been closed, the drop-off storage areas became illegal dumps, sources of projectiles for the next hurricane season. The Saint Martin collectivity had neither the technical nor the human resources for cleaning and collecting these dumps. Specific procurement procedures had to be drawn up for each cleaning operation.

From the beginning of 2018, the official waste management system started to run normally again, as before Irma. It was overwhelmed very quickly by the stream of waste that continued to be produced. This situation led to an informal waste management system. The new system was set up by a number of new actors: new citizen associations, actors who had to assume new responsibilities and cleaning campaigns organized by the community with the population's participation. They appeared spontaneously in the face of the need to clean up areas that were difficult to access, such as the seabed, mountains, natural areas, etc. Pre-existing informal actors and waste recycling and reuse streams also increased their activities as a result of this opportunity. Among the local recycling actors, we note the presence of three building and public works companies possessing crushers for grinding concrete. However, this activity was marginal and not officially recognized on the island. According to local actors' estimates, only 10% of the material was recycled on embankment, earthmoving and road base projects, 60% of the concrete was used to create surfaces between layers of household waste on the landfill and 30% was illegally dumped in the countryside [41].

Reusable building materials (steel sheeting and timber) were recovered by informal networks controlled by the Haitian and Dominican communities and sent back to their home countries. According to interviews held with heads of building companies, before Irma they sent back containers with building materials once or twice a year. After Irma, this export flow increased to several containers per week. If, quantitatively, this informal sector did not represent a great deal, it still played a role on materials that were exported, i.e., materials that left the island system [41]. In his works, [48] also calls for the need to integrate the informal recycling sector into the formal waste management system in order to make the social metabolism more circular. A first step is to improve our understanding of this sector in order to recognize its importance and inform public policies around ecological sustainability. Further research is needed not only in low-income countries, but also in high-income countries where informal recycling is becoming a growing phenomenon, that finds local authorities unprepared.

The importance of informal networks in disaster waste management has already been observed in several territories, such as Haiti after the 2010 earthquake, where 57.5% of the total volume of waste produced was managed by the informal sector and civil society [49,50]. These informal networks represent streams with interesting potential from the perspective of circularizing waste flows in Saint Martin's metabolism. They need to be accompanied by the authorities both financially and technically, so that they can last over time on the territory.

5. Conclusions

In conclusion, the analysis of the evolution of Saint Martin's metabolism following the impact of hurricane Irma shows a strong variation in its three short-term dimensions. Faced with the intensity of waste flows, a new spatial structure and a new system of actors reinforced by external resources was set up in order to control the waste streams. This change led to a transformation in the system's operation when compared to the way it operated previously. Once the crisis period was over, the waste management system did not return to its initial mode of operation. The intensity of the waste flows that continued to be generated remained much higher than before Irma. The capacities of existing official infrastructures proved to be insufficient for absorbing all the new waste flows, and this resulted in their spatial dissipation to illegal dumps or via informal streams. As a result, the metabolism evolved on the three dimensions under study: intensity, spatial dimension and actors and techniques.

These evolutions led to a lasting transformation of waste stocks. Most of the waste generated by Irma was buried, particularly furniture and electrical/electronic waste collected together during the crisis period. The condition for having this waste recovered by an eco-organization is that it is sorted and clean, an operation that is extremely difficult to set up during a crisis period if it has not been planned beforehand. Under these conditions, according to the manager of Verde SXM company, the Grandes Cayes landfill lost three years of its life as a result of Irma [41]. Three years after the crisis, new post-Irma waste flows continue to be generated by operations for cleaning, demolishing or reconstructing abandoned houses—operations that have only been 50% completed at present. These operations were essentially focused on building and public works.

On the other hand, the permanent transformation of the waste flow's circulation is less certain, a phenomenon that can be partly attributed to informal streams. The waste flows from the ELV (End-of-Life Vehicles) and BPHU (Out-of-Service Pleasure Boats) sector are the only ones whose structuring was supported by the authorities, through the assistance of DEAL Guadeloupe. The management of hazardous waste is the state's responsibility. After Irma, a DEAL territorial unit was created in Saint Martin with a risk and pollution officer, an evolution that has represented a lasting transformation in the management of hazardous waste flows. Two extra garages were installed on the territory for handling ELVs and accelerating their decontamination, crushing and compacting operations. Thanks to these measures, the collection rate went up from 40 ELV per month to around 200 ELV per month during 2018, but it did not reach the target imposed by the DEAL of 400 ELV per month. In 2019, one of these two garages was closed following controls due to non-compliance with pollution regulations, but the garage at Grandes Cayes is still in operation. Hence, by March 2019, 2900 ELV out of a total stock of 50,000 were evacuated from the territory (2000 before Irma). In 2019, a number of ELVs were identified on public land that had not yet been collected, and there were also a number of ELVs stored on private property that the population had kept for selling their spare parts. Concerning out-of-service pleasure boats, public tenders have been issued to find an operator capable of decontaminating and dismantling them. By 2019, 170 wrecks have been mapped and located, but they were still awaiting processing due to lengthy administrative procedures [41]. On the other hand, and despite the support of the Saint Martin prefecture, which recognizes the importance of structuring this type of activity, building and public works waste stream still operates under unofficial conditions. Even so, the system of actors in this sector has undergone a transformation, caused by the appearance of new actors or by the consolidation of a certain number of pre-existing actors. The management of the sector is under the responsibility of the collectivity. As far as management of household waste is concerned, it has returned to its initial mode of operation.

The lack of structured streams in Saint Martin before Irma and the difficulty in incorporating them into the structure of the official system after the crisis have given rise to difficulties in monitoring and accounting for these waste flows and to a low recycling rate. Some exports of waste were reported by the Verde SXM company. Up to 2019, two ships of 3700 tons each of crushed scrap metal and one container of 300 tons were shipped to the north of France [41]. Two years later, the Grandes Cayes ecosite had still not returned to normal operation, as it was still processing waste caused by Irma.

The Saint Martin case study highlights a metabolism that remains largely internalized. Despite its transformation following the disaster and the appearance of a few new recycling or re-use streams, waste flows remain relatively linear. This observation underlines the importance of working firstly on the circularity of these flows internally, and secondly on the scale of the Caribbean region, thereby tending toward outsourcing.

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