A Framework to Design a Municipal Decision Support Tool for Cyclone-Induced Marine Flooding Emergency Management at Reunion Island

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A FRAMEWORK TO DESIGN A MUNICIPAL DECISION SUPPORT TOOL FOR CYCLONE-INDUCED MARINE FLOODING EMERGENCY MANAGEMENT AT REUNION ISLAND

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KEY WORDS

Coastal hydrodynamic modelling; wave overtopping; marine flooding mapping; decision-making

ABSTRACT

Marine flooding by wave overtopping is quite regular at Reunion Island, in particular during cyclonic events. Given the limited geographic scale of this phenomenon, the municipalities are often at the forefront to assure the protection of the population. Thus, there is a crucial need for the municipalities to have flexible and practical tools at their disposal to interpret the marine forecasts in terms of flooding impact on their territory and enhance their capacity to anticipate and organize their operational response. Here, we propose a framework to design a dedicated GIS-based decision support tool (the Graduated Intervention Plan) based on feedback analysis, field observations and state-of-the-art coastal hydrodynamic modelling. The method notably relies on a pre-calculated database of 500 synthetic events simulated with a complete chain of hydrodynamic models. The analysis of the relationship between marine conditions, overtopping discharge volumes and water propagation processes leads to the constitution of (1) a set of flooding maps delimiting the spatial extent of exposed areas given increasing levels of marine conditions and field observations (2) a list of operational actions associated to each level (roads closure, etc.). The whole process was conducted in a collaborative manner with the municipal services of Sainte-Suzanne city (northern coast of Reunion Island) and the final tool is included in a multi-hazard decision support tool taking into account river flooding and runoff. It was tested during a crisis simulation exercise with very good feedbacks.

1. INTRODUCTION

In a context of changing climate, the perspective of increasing cyclone-induced marine flooding frequency or intensity is a matter of concern, especially when the growing urbanization rises the proportion of people living in low-lying coastal regions. The development of efficient early warning systems (*Lumbroso et al., 2017*) and dedicated crisis management strategies is complementary to prevention and preparedness measures. Given the limited geographic scale of marine flooding events, the municipalities are often at the forefront to assure the protection of the population. Thus, they have a crucial need of dedicated and practical tools to understand the ongoing physical processes and enhance their capacity to anticipate.

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Operational forecast systems of cyclone-induced waves and water levels are now fairly standards since the 90' (*Jelesnianski et al., 1992; Daniel et al., 2009, etc.*) and current efforts of operational agencies aim to improve the forecast accuracy of probabilistic sea water levels by coupling tide, storm surge, waves and induced wave setup models (*Taylor and Glahn 2008; Davis et al., 2010; etc*.). On the other hand, the operational forecast of marine flooding still poses different challenges. Actually, the numerical simulation of the coastal flooding (overflowing plus wave overtopping) at a resolution useful for flood hazard assessment is still hampered by high computation time (*Nicolae Lerma et al., 2018*) despite ongoing efforts to develop new generations of efficient phase-resolving models (*Filippini et al., 2018*). Promising approaches rely on the analysis of existing databases of pre-calculated high-fidelity simulations to derive statistical models (or "surrogates") that are able to estimate quickly the marine conditions or flooding extent directly from the storm parameters. Existing techniques rely on kriging, artificial neural networks or Bayesian networks. In cyclonic-prone areas, *Rohmer et al. (2019)* proposed a method to derive overtopping characteristics (timing and volume) thanks to a random forest technique. This kind of sophisticated tool is dedicated to expert users but is not directly usable by municipal services, especially for small cities with limited resources as often encountered in tropical islands like La Reunion.

The analysis of the crisis management organization of Sainte-Suzanne city (North of Reunion Island), as well as the lessons learnt from crisis simulation exercises (*Sauvagnargues et al., 2018*), demonstrated the need for the members of the municipal crisis unit to have pragmatic tools linking the weather and marine forecasts with potential impacts on land and appropriate operational responses (*Sauvagnargues et al., 2017*). The Graduated Intervention Plans (GIPs) are cartographic documents used to structure the operational response of municipal crisis units in different levels of gravity regarding various risks presents on the territory. To be operational, this cartographic support relies on a dual approach combining: (1) capitalized experience within each territory studied in terms of impact of hazards (practices, feedback, archives, etc.) (2) the representation of the spatial extent of potentially impacted areas, structured in gravity levels and built on modelling results and/or existing knowledge. If this type of tool is widely used for river flooding (*Ayral et al., 2015; Sauvagnargues et Ayral, 2015*), to date and to the authors' best knowledge, it was not yet applied for marine flooding in France or in the Overseas Territories. The difficulty in the case of marine flooding is the scarcity of historical events (especially for cyclones) and the fact that the physical processes are governed by multiple parameters (waves, tide and storm surge). This last aspect complicates the determination of the criteria of transition between different levels of gravity, especially for non-expert users.

The objective of this study is to present a method to produce GIPs dedicated to cyclone-induced marine flooding for the pilot site of Sainte-Suzanne city at Reunion Island. It is based on both feedback analysis, field observations and state-of-the-art coastal hydrodynamic modelling. The method notably relies on a pre-calculated database of numerous synthetic events simulated with a complete chain of models. The analysis of the relationship between marine conditions, overtopping discharge volumes and flooded areas leads to the constitution of marine flooding maps, delimiting the extent of impacted areas given different increasing levels of marine conditions, and coupled with a list of operational actions associated to each level. The criteria of transition between the different levels connect operational marine forecasts with field observations and historical benchmarks, thus enabling different levels of use and anticipation. This tool was tested and validated during a crisis simulation exercise on site.

The paper is organized as follows. Section 2 presents the study site of Sainte-Suzanne city. Section 3 describes the complete chain of models and the constitution of the synthetic database. Section 4 explains the principles of the GIPs, i.e. the building of marine flooding maps, the determination of associated operational actions with the collaboration of the municipal services, and the test of the GIP during a crisis exercise on site. Finally, section 5 gives the conclusions and perspectives to adapt the method for other territories.

2. STUDY SITE: PROCESSES AND CRISIS MANAGEMENT PRACTICES

2.1 Configuration and marine flooding processes

Reunion Island is a French Overseas Department located in the Indian Ocean, east of Madagascar (*see inset in Fig. 1*). Due to the mountainous nature of the island, 80% of the population is concentrated near the coastline, thereby resulting in high vulnerability to tropical cyclones. The tide is micro-tidal, with a maximum tidal range of approximately 60 cm (at the tide gauge Pointe-des-Galets, *French Hydrographic Service 2014*). The lack of a continental shelf around the island reduces the generation of atmospheric storm surges that remain moderate and localized near the cyclone's eye. This setting, associated with the high topography of sea fronts prevents the coastal areas from marine flooding by overflowing. In contrast, it increases the potential impact of waves that are not dissipated before reaching the coast (except in the few reef zones) and whose breaking on the steep slopes may generate considerable overtopping. Thus, the main drivers of cyclone-induced marine flooding at Reunion Island are the energetic (high and/or long) waves. However, the variations of seawater levels may facilitate wave overtopping. Current operational forecasts at Reunion Island provide nearshore waves characteristics (significant wave height: *Hs*, pic period: *Tp*, and pic direction: *Dp*) but no seawater levels (SWL) yet.

Sainte-Suzanne city is located along the pebble coast in the northeast part of the island (*see Fig. 1*). In recent years, the city centre has been regularly affected by marine flooding, e.g., cyclones Dumile in 2013, Gamède in 2007, Dina in 2002, Clotilda in 1987, etc. Experience feedback and simulation results indicate that water discharge from wave overtopping first affects the sea-front parking area before flowing along December the 20^{th} Street and penetrating into the perpendicular streets Hippolyte Piot, Cayenne and La Gare (*Fig. 1*). Small low-lying urban areas around the emergency centre and the city-centre buildings (school and city hall) behind the parking area can be quickly flooded by more than one meter of water. The artificial lagoon lying north of the eastern side of December the 20^{th} Street protects the buildings situated behind (Bertin Street and Desprez neighbourhoods) and enables the evacuation of a large part of the water coming from the seafront.

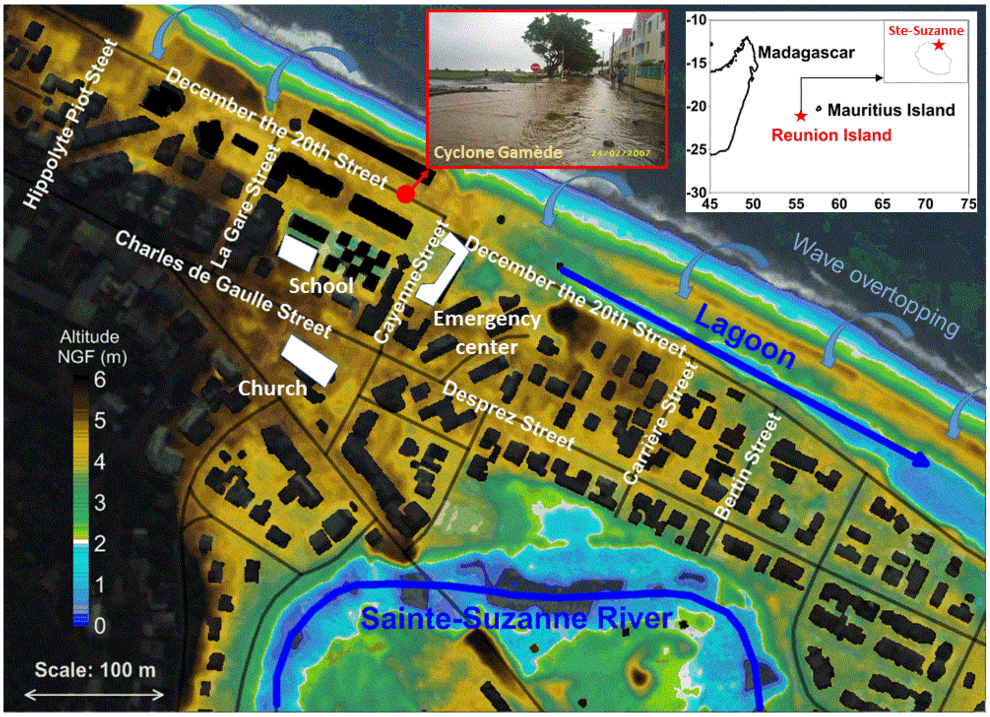


Figure 1: Topography of Sainte-Suzanne city derived from high-resolution LIDAR (IGN) data with main streets and critical buildings of the sea-front quarter.

2.2 Crises management practices

In France, the responsibilities of crisis management are shared between Ministries, Zones, Departments and Municipalities. At local level, the Municipal Safeguard Plan (PCS) is a planning and organization instrument designed to anticipate dangerous situations in order to ensure the protection and safety of the population. It aims at preparing the actors involved in the crisis management to reduce uncertainties and improvised actions as much as possible (*DDSC, 2005*). The PCS of Sainte-Suzanne includes the description and mapping of the hazards (when possible), the alert levels (when available), the instructions given by the authorities to the population and the general organization of the crisis management cell (organization of the Communal Command Post or PCC, reflex forms, resources as emergency shelters, materials, etc.). The analysis conducted by *Sauvagnargues et al. (2017)* highlighted that the characteristic of marine conditions leading to wave overtopping and the corresponding exposed areas were not well known. The current practice of the municipal services consists in sending employees to observe different strategic locations of the city centre during an event in order to extrapolate a "mental map" of the marine flooding based on their knowledge of the territory and the memory of past events. This practice may be efficient but it is not sustainable as it only relies on personal experiences and skills. More generally, there is also a need to enhance the evacuation modalities, notably through (1) the knowledge of the amount of inhabitants per quarters or exposed areas (2) the organization of the alert of the population (3) the identification of the level of exposure of the emergency shelters.

3. MARINE FLOODING MODELING AND CONSTITUTION OF THE DATABASE

3.1 Modelling chain

3.1.1 Coastal waves and water levels

The wave model (*see Fig. 2A*) is a combination of a two-way nested Wavewatch III modelling framework (*Tolman 2014*; hereinafter denoted WW3) enabling the offshore waves generation and propagation to Reunion Island coastlines. The version 4.18 of WW3 is used with the source term package described by *Ardhuin et al. (2010)*. The first grid (R1) covers a large part of the South Indian Ocean with a regular resolution of 0.1° while (R2), centered on Reunion island, is composed of finite elements whose resolution reach about 300 m at the coast. The regional hydrodynamics (seawater level and currents) are computed with MARS (*Lazure and Dumas 2008*) on a regular grid with the same extent as R2 at a resolution of 100 m (*see Fig. 2A*) based on tidal components (FES2004; *Lyard et al.*, 2006). We use the 2DH version of the model, which resolves the Saint-Venant equations governing horizontal free-surface flows in two dimensions, after vertical integration of the Navier Stokes equations. The bathymetric data used come from ETOPO1 with a spatial resolution of 1 minute (*Amante and Eakins, 2009*) as well as the bathymetric measurements from the French Naval Hydrographic and Oceanographic Service near the island.

3.1.2 Marine flooding

Wave overtopping discharge is calculated with profiles of the nonhydrostatic model SWASH (*Zijlema et al., 2011; Suzuki et al., 2012*) at a resolution of 1 m. The profiles are determined by splitting the coastline into homogeneous segments in terms of topo-bathymetry (see Fig. 2C). For each segment, the model is forced with time series of water levels at a 50-m depth, including both seawater level variations (tide and storm surge) and waves. These time series are established by extracting the water level from MARS-2DH and the wave parameters from WW3 at 10-minute intervals and reconstituting a time series of the total water level variations at high frequencies (at 2 Hz) using the WAFO toolbox (*Brodtkorb et al., 2000*). The model MARS-FLOOD is used to reproduce the inland propagation of overtopping. It is an extension of MARS-2DH, including extended functionalities to account for flooding processes, such as breaching and hydraulic connections (*Rohmer et al., 2018*). The grid of MARS-FLOOD (see Fig. 2C) is centred on the city center with a regular spatial resolution of 4 m, which enables the model to properly represent streets and buildings. The topo-bathymetric data used for the SWASH and MARS-FLOOD models comes from the Litto3D program (high-resolution LIDAR data, http://professionnels.ign.fr/litto3d). Here, we apply the method described by *Le Roy et al. (2015)* to construct a DTM including the buildings likely to obstruct water flow and to filter out any vegetation or cars in the raw model.

3.1.3 Validation with reanalyzed data

We apply this chain of models to two recent cyclones passing within 200 km from Reunion Island: Dumile in 2013 and Dina in 2002 (*see Fig. 2A*). Dina was the most damaging event since the early 2000s. The southwestward track passed 65 km north of the island with a maximum wind intensity of 100 kt. Dumile was less damaging, with a southward track that passed 100 km west of the island and a moderate wind intensity approximately 70 kt. To force the models, the wind fields are calculated from best-track data of Météo-France (describing time-varying track, intensity, size and shape of the cyclone) with the model MESO-NH following the method described by *Lecacheux et al. (2018)*.

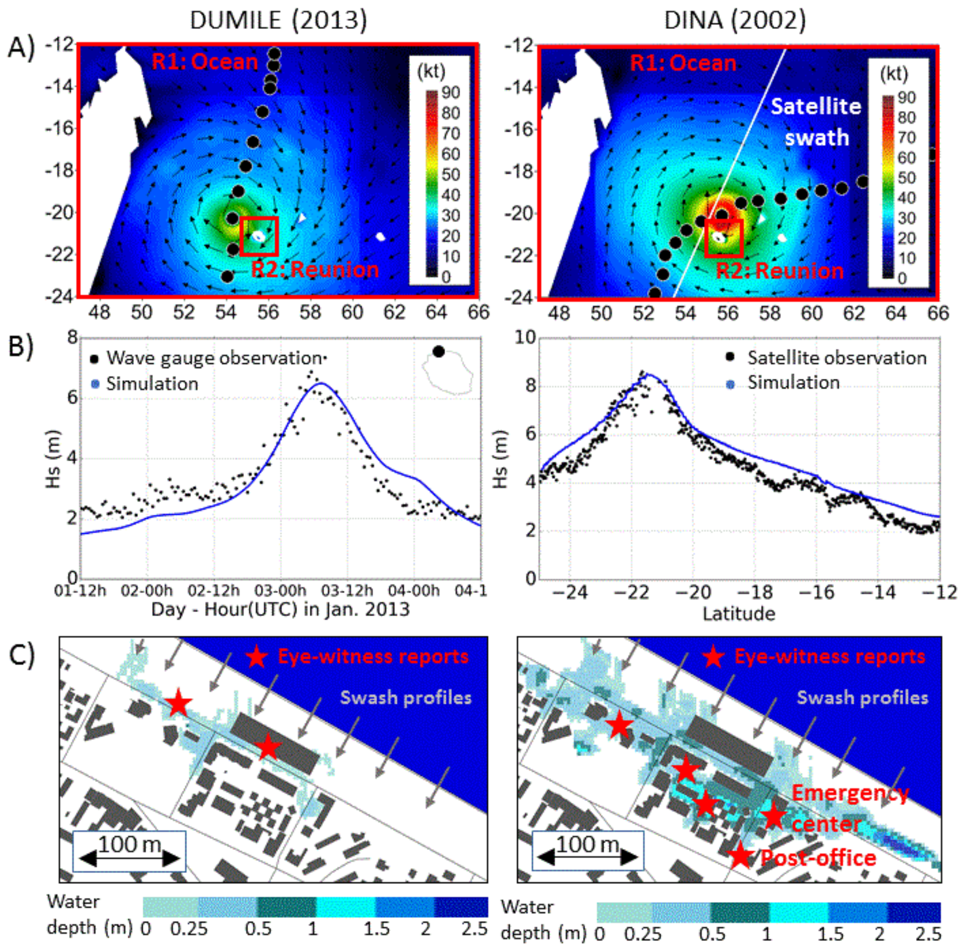


Figure 2: A) Grid extent with tracks (black dots), wind intensity (colors) and directions (arrows) of cyclones Dina and Dumile calculated with MESO-NH from best-track data. B) Comparison between simulated wave heights with observations from satellite altimetry on January the 23rd at 06 UTC (Dina) or time-varying observations from buoy RN4 (Dumile). C) Position of the SWASH profiles and comparison between simulated flooding with eyewitness accounts.

The simulation-based estimates of the seawater levels (including tide and surge) was crosschecked with data from the tide gauge Pointe-des-Galets with good fitting and errors under 10 cm (the data is not presented here). Fig. 2B shows the comparison between simulations and observations of wave heights with satellite altimetry from the CERSAT (Dina) or buoy measurements (Dumile) depending on the data availability. For both cases, the comparison is very satisfactory with less than 10% error for the peak wave heights. Concerning marine flooding, we compared the simulation results with local eyewitness accounts enabling an estimation of the extent of the inundation (Fig. 2C). For Dina, the simulated marine flooding extent agrees very well with the local eyewitness accounts. The first row of buildings was flooded and the water penetrated into the perpendicular streets to inundate the second row of buildings, the emergency centre, and the post office. For Dumile, the simulated marine flooding was slightly overestimated but remains in agreement with a limited flooding event.

3.2 Database of synthetic events

The database gathers 500 synthetic cyclones derived from historical cases (*see Fig.3*). First, 125 systems analysed between 1981 and 2016 are selected. For each track, the position where the system reached the maximum intensity is placed on the centre of Reunion Island. Then, each track is shifted by randomly choosing a direction (between 0° and 355°) and a distance from the centre of the island (between 0 km and 400 km). This range of distances enables the simulation of both scenarios that are likely to generate major overtopping in Sainte-Suzanne and scenarios with low to moderate waves that do not generate overtopping. For each scenario (describing time-varying track, intensity, size and shape of the cyclone), the marine flooding of Sainte-Suzanne is simulated using the modelling method presented in *section 3.1* (with the series of models Meso-NH, WW3, MARS and SWASH) considering random tide level time series and large-scale conditions. Among the 500 initial cases, 136 generated wave overtopping with an inundation of Sainte-Suzanne city.

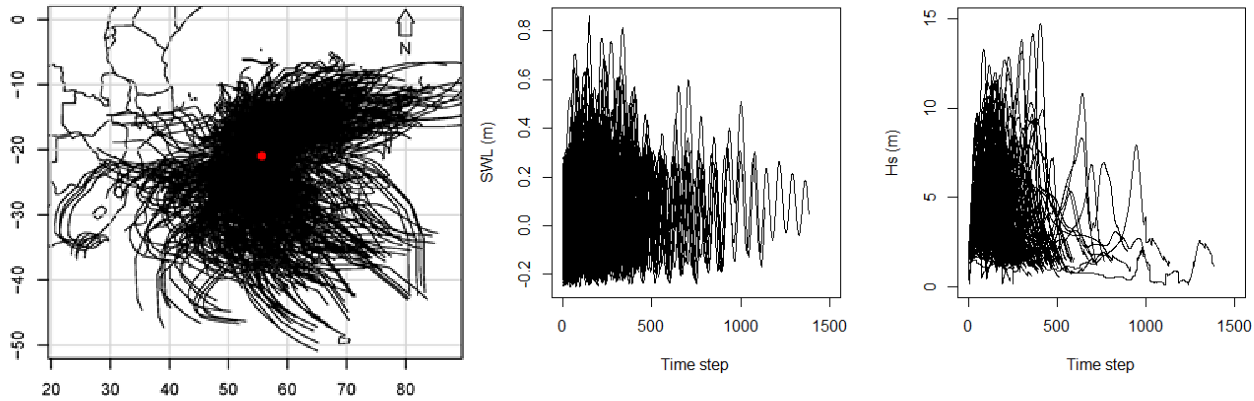


Figure 3: 500 synthetic tracks constituting the database with examples of 30 time series (presented on a normalized time index) of significant wave heights (Hs) and seawater levels (SWL) at 50m depth in front of Sainte-Suzanne city.

3.3 Sensitivity analysis of the governing parameters

The relative importance of the marine conditions (extracted at 50m-depth in front of our site) in the is studied with respect to the log-transformed of the maximum cumulative overtopping discharge volume V (i.e. $\log_{10}(V+1)$). To do so, the combination of the pre-calculated V values considering the 500 synthetic tracks and their corresponding marine conditions (maximum Hs and associated Tp and SWL at the same time) are used as training data of a regression random-forest model (*Breiman, 2001*). Full details of this implementation is provided in *Rohmer et al. (2019)*. Using this statistical model, the importance of each governing parameter can be studied with respect to V. Fig. 4A provides the measure of variable importance using the permutation-based method of the random forest (e.g., *Wei et al., 2015*). This clearly confirms the very high importance of the wave parameters, and more specifically of Hs, as mentioned is *section 2*.

The analysis is completed by the Individual Conditional Expectation plots of *Goldstein et al., (2015)* in Fig. 4B, which depicts the functional relationship between the predicted value of the log-transformed of V and maximum Hs given the values for the other variables. This clearly outlines the step-like influence of Hs, i.e. the existence of a threshold at about 5m above which the overtopping volume increases correspondingly with an increase of Hs, and a horizontal asymptote at ~10m. For Hs values under 4-5m, the other parameters, notably the water level (tide and atmospheric surge), may have a greater influence to discriminate between flooding and non-flooding events.

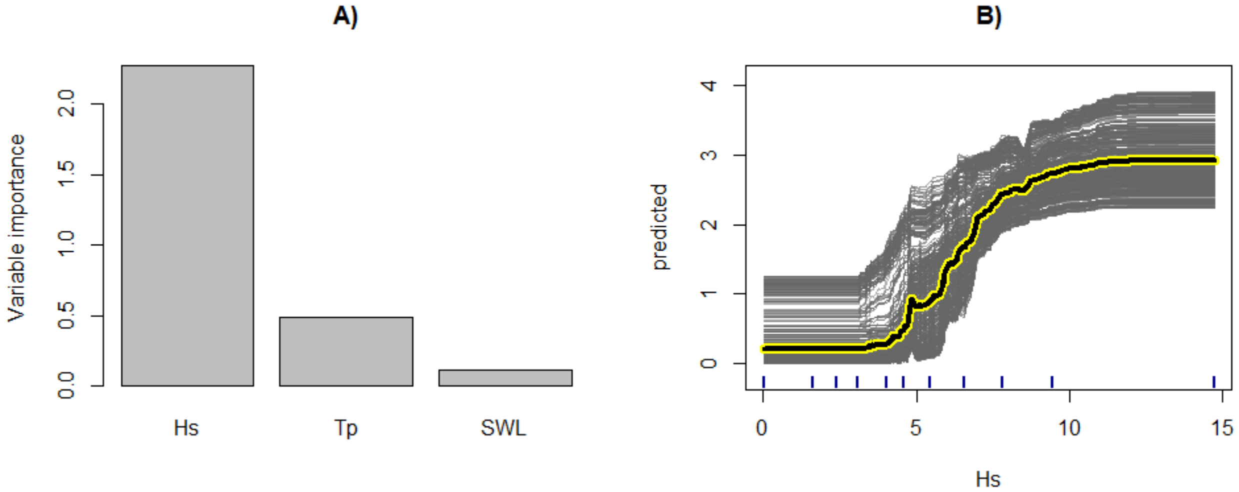


Figure 4: A) Importance measure for each variable (Hs, Tp, SWL) derived from a random-forest model trained using the synthetic cyclones B) Functional relationship between the predicted value of the log-transformed of V and Hs. The yellow line indicates the average effect of Hs.

4. BUILDING THE GRADUATED INTERVENTION PLAN (GIP)

4.1 Analysis of the database and determination of graduated flooding maps

The set of synthetic events is analyzed with a coupled analytic and GIS mapping method in terms of overtopping volumes, flood spatial extent and maximum water depths on land. As the sensitivity analysis shows that the wave height is the main parameter controlling the overtopping discharge volume (and then the extension of marine flooding), we focus only on the relationship between the maximum wave height reached during the event (at 50m-depth in front of Sainte-Suzanne) and the maximum flood spatial extent on land. This choice is also motivated by (1) a concern of simplicity for the end-users who need easy-to-read tools (2) the fact that there is not yet public operational forecast of seawater levels at Reunion Island.

Data mining of the simulations enables to classify the results into different clusters depending on Hs thresholds and controlled by the topography (notably the presence of low-lying basins) and the drainage capacity of the artificial lagoon. The bivariate diagram (*Fig. 5*) reveals four groups of equivalent flood spatial extent associated with ranges of Hs:

- ✓ The first cluster (Hs_{max} between 4m to 6m) corresponds to simulations leading to the first projections of water and pebbles on the waterfront, mainly on the parking of the city centre, without any flooding of the buildings.
- ✓ The second cluster (Hs_{max} between 6m to 8m) illustrates the simulations leading to flood propagation in the Cayenne Street with low water depths.
- ✓ The third cluster (Hs_{max} between 8m to 10m) represents the intensification of marine conditions with flows penetrating further the main streets (Cayenne, La Gare and Hippolyte Piot) and reaching the city centre. The low-lying basins are saturated with upper water depths and a part

of the water is drained by the lagoon that overflows in front of the Bertin Street and Desprez neighbourhood.

- ✓ The fourth cluster (Hs_{max} above 10m) includes the simulations whose flooding exceeds the Charles de Gaulle Streets with water depths approaching capacity storage, and water flowing toward the river Sainte-Suzanne.

Using a GIS method, we delimit the boundaries or contours of each cluster aided by the simulated flood maps and an analysis of the volume storage capacity through topographic ridges (like roads or streets and troughs). The contours are established with a safe approach to encompass all the scenarios of flooding events constituting the cluster and taking into account the possible variations of wave period and seawater level as well as the various kinetic and the duration of the events. Finally, despite the simplification of the analysis with one variable (maximum Hs), the corresponding maps are robust thanks to the large amount of realistic events constituting the dataset.

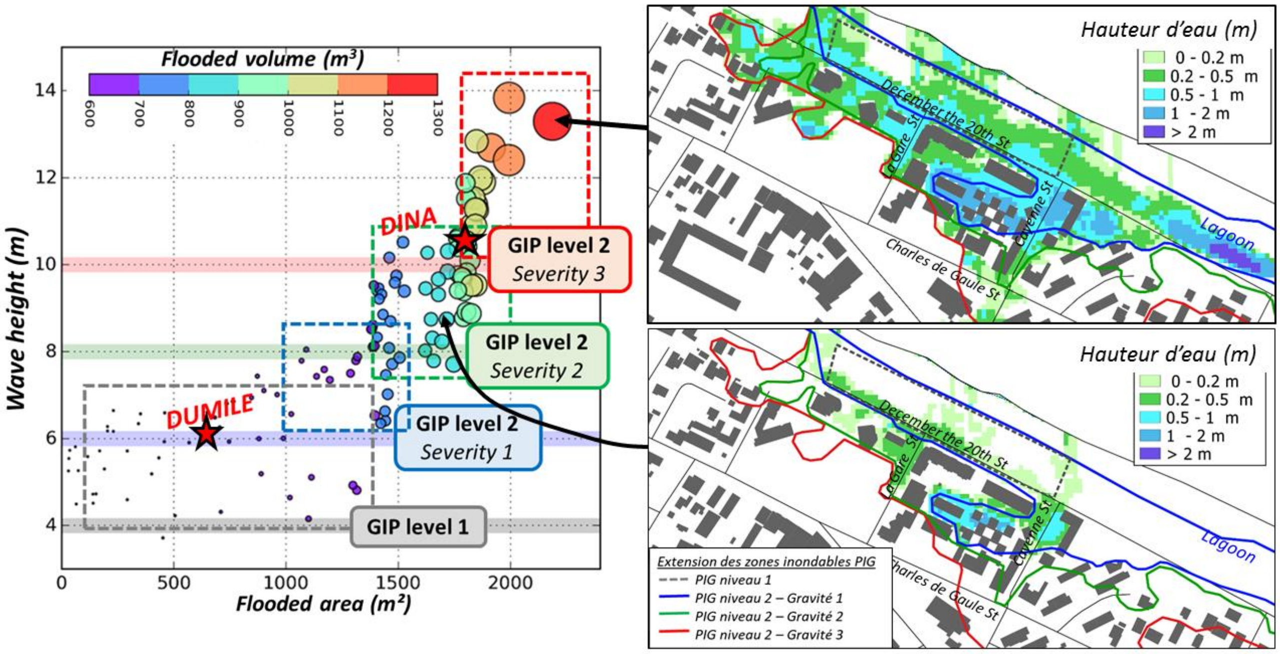


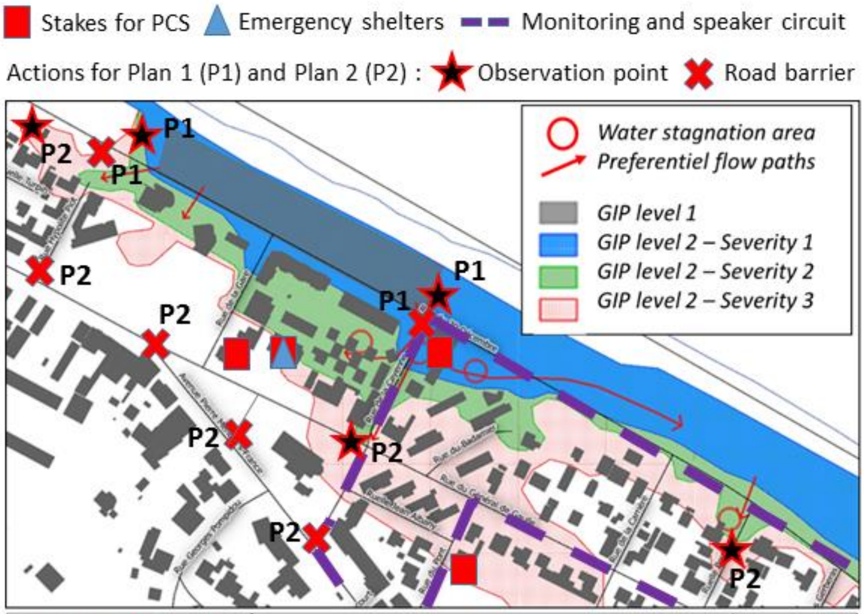
Figure 5: Right panel: Relationship between maximum coastal wave heights (at 50m-depth) with maximum flooded areas and overtopping volumes in the city centre of Sainte Suzanne. Left panel: Two examples of flood maps compared with the GIP contours.

4.2 Collaborative work with the municipality and determination of the operational responses

The transposition of the flooding maps into a Graduated Intervention Plan (GIP) was conducted in close collaboration with the municipal services, notably through several on-site visits. The maps and a general outline of the action forms were provided to the municipality. From these documents, the technical services specified the different levels of the plan, and adapted the boundaries of the maps and the associated action forms to fit with the particularities of the territory and their own practices. This two-step process ensures the global relevance of the GIP from an operational point of view.

At the end, two levels have been considered: one corresponding to the first visible impacts on the seafront parking, and a second (decomposed in 3 levels of severity) corresponding to the flooding of buildings in the city center (*Fig. 6*). The transition conditions between the different levels rely on both direct observations of the consequences on the field (to fit with the current practice of the services) and the thresholds of wave heights that can be inferred from the operational forecasts distributed by Météo-France (http://www.meteofrance.re). In addition, historical benchmarks of past major events are indicated in order to give a mental representation of the importance of the current event. These different keys of reading enables one to use the GIP with different levels of anticipation:

- ✓ During the early-warning period, to estimate the potential exposed sectors;
- ✓ During the crisis, to spatially extrapolate the observations made on strategic monitoring points.



Graduated Intervention Plan (GIP)		Field observations	Wave height (m) range	
Coastal flooding plan - Level 1		First wave overtopping and pebbles (or stones) projections on the waterfront (city center's parking)	> 4 m	Felleng
Coastal flooding plan - Level 2	Severity 1	First buildings to be flooded in the city center : School, Emergency center, town hall	6 m - 8 m	Bejisa Dumile
	Severity 2	Bertin street behind the lagoon, first buildings along 20 december street and the Desprez neighborhood are affected by flood	8 m - 10 m	Gamède
	Severity 3	Flood reaches buildings of Desprez neighborhood, inundation and flow path throught Cayenne street exceeds General de Gaule street.	> 10 m	Dina

Figure 6: Map aggregating the different levels of the Graduated Intervention Plan (GIP) of Sainte Suzanne city centre with the transition criteria (field observations, Hs thresholds and benchmarks).

For each level of the GIP, specific actions are declined and the information is reported on the maps: the potential impacted area, the territory's monitoring points, the road closure points, the pre-established circuit of the sound car (mobile warning system). As the decision and the allocation of means for the evacuation is not under the responsibility of the municipality level, this type of action is not directly reported in the GIP. However, the graduated flood maps will enable the municipality to (1) encourage the exposed population to join the emergency shelters (2) transfer precise information to the department level to better target and anticipate an official evacuation. The population count per district and exposed areas also facilitates the dimensioning of the means.

4.3 Testing the GIP during a crisis simulation

The marine flooding GIP is included within a global multi-hazard GIP articulating river flooding, runoff and marine flooding plans for cyclonic events (*see Fig. 7*). In order to facilitate the appropriation of the GIP developed previously, a simulation was carried out in October 2017 as part of an in-situ crisis management exercise. A complete scenario of cyclonic event was prepared for the municipality with the combination of an intense rainy event 24 hours before the arrival of the cyclone close to the coasts of Reunion Island. During the exercise, the municipality had to deal with the runoff issue while anticipating the marine flooding hazard thanks to marine. The GIP proved to be very useful and during the debriefing, several discussions emerged, notably:

- ✓ The safety and dimensioning of emergency shelters (sometimes located in flood-prone quarters) and a better anticipation for their opening.
- ✓ The need to anticipate a withdrawal room for the communal crisis unit.

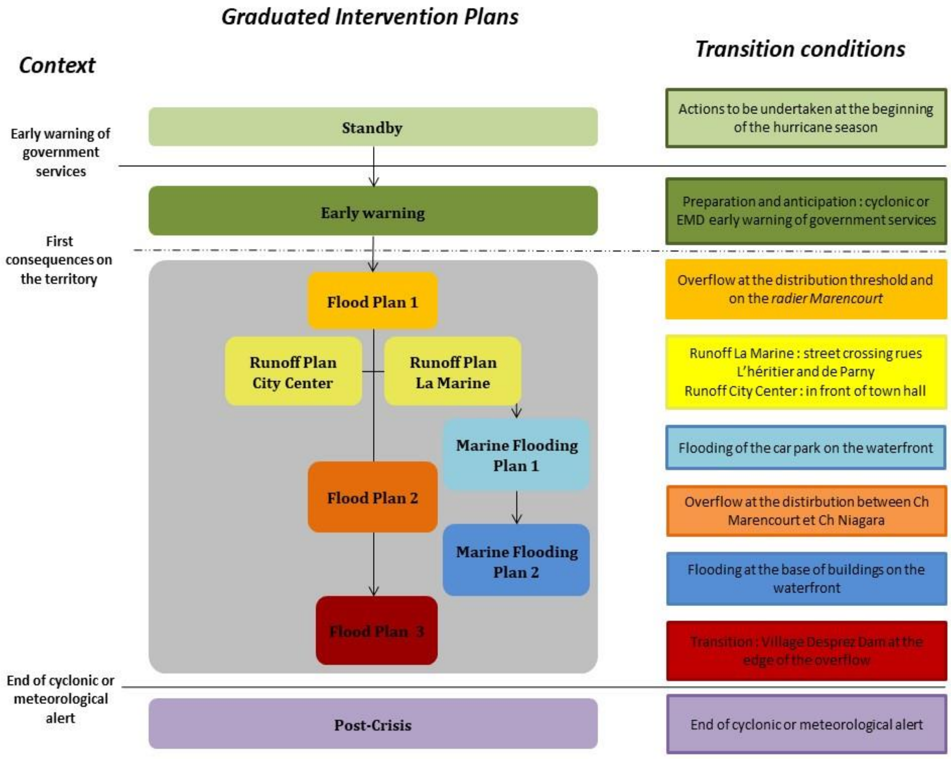


Figure 7. Complete GIP for a cyclonic event including runoff, marine flooding and river flooding.

5. CONCLUSIONS

In this paper, we present a method to produce a municipal Graduated Intervention Plan (GIP) dedicated to cyclone-induced marine flooding emergency management. It relies on feedback analysis, field observations and the constitution of a precalculated database of flooding events based on state-of-the-art coastal hydrodynamic modelling. The plan couples a set of flooding maps indicating the exposed areas for increasing levels of marine conditions and field observations with a list of predetermined operational actions associated to each level.

Despite the significant effort required to produce the pre-calculated database, the use of numerous synthetic (but realistic) events enables a robust sensitivity analysis of the governing parameters leading to marine flooding to (1) simplify the interpretation and understanding of non-expert end-users (2) construct a robust set of maps taking into account various sources of uncertainties (seawater level variations, event duration, etc.). The different reading keys (wave forecast, field observations, and historical benchmarks) enables one to use the GIP with different levels of anticipation.

More generally, the whole method can easily be adapted to other territories, scales and any marine flooding processes (overflowing and overtopping) through the implementation of suitable marine flooding models validated against past events and the early involvement of stakeholders.

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REFERENCES AND CITATIONS

Amante, C., and Eakins, B.W., 2009. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24, 19 pp.

Ardhuin, F., Rogers, W.E., Babanin, A.V., Filipot, J., Magne, R., Roland, A., Van der Westhuysen, A., Queffeulou, P., Lefevre, J., Aouf, L., Collard, F., 2010. Semiempirical dissipation source functions for ocean waves. Part I: Definition, calibration, and validation. J. Phys. Oceanogr. 40(1), 917– 1,941.

Ayral P.-A., Ferry G., Garcia S., Laforgue P., Piatyszek E., Saint-Pierre L. & Schmidt I., 2015. Elaboration du Plan Communal de Sauvegarde Multirisques de la ville d'Alès : Retours d'expérience, in Plans Communaux de Sauvegarde et outils de gestion de crise, Presses Universitaires de la Méditerranée, 14p.

Breiman, L., 2001. Random forests. Machine learning, 45(1), 5-32.

Brodtkorb, P.A., Johannesson, P., Lindgren, G., Rychlik, I., Rydén, J., Sjö, E., 2000. "WAFO - a Matlab toolbox for analysis of random waves and loads", *Proceedings of the 10th International Offshore and Polar Engineering conference*, Seattle, Vol III, pp. 343-350.

Daniel, P., Haie, B., Aubail, X., 2009. Operational forecasting of tropical cyclones storm surge at Météo-France. Marine Geodesy, volume 32, Issue 2, Special issue: storm surges around the globe.

Davis, JR, Paramygin, VA, Forrest, D, Sheng, YP, 2010. Probabilistic simulation of storm surge and inundation in a limited resource environment. Mon Wea Rev 138(7):2953–2974.

DDSC (DIRECTION DE LA DEFENSE ET DE LA SECURITE CIVILES). 2015. *Plan communal de sauvegarde, guide pratique d'élaboration.* Paris, 202p.

Filippini, A.G., De Brye, S., Perrier, V., Marche, F., Ricchiuto, M., Lannes, D., Bonneton, P., 2018. UHAINA: A parallel high performance unstructured near-shore wave model. XVèmes Journées Nationales Génie Côtier – Génie Civil La Rochelle, 29 au 31 mai 2018.

Jelesnianski C.P. and J. Chen and W.A. Shaffer, 1992: SLOSH: Sea, Lake and Overland Surges from Hurricanes. NOAA Technical report NWS 48, Dept. of Comm. NOAA, 71pp.

Lazure, P., and Dumas, F., 2008. An external–internal mode coupling for a 3D hydrodynamical model for applications at regional scale (MARS). Advances in Water Resources 31, 233–250, 2008.

Le Roy, S., Pedreros, R., André, C., Paris, F., Lecacheux, S., Marche, F., Vinchon, C., 2015. Coastal flooding of urban areas by overtopping: dynamic modelling application to the Johanna storm (2008) in Gâvres (France). Natural Hazards and Earth System Sciences 15, 2497–2510. https://doi.org/10.5194/nhess-15-2497-2015.

Lecacheux, F. Bonnardot, M. Rousseau, F. Paris R. Pedreros, A. Nicolae Lerma, H. Quetelard, D. Barbary, 2018. Probabilistic forecast of coastal waves for flood warning applications at Reunion Island (Indian Ocean). *Journal of Coastal Research,* Special Issue No. 85, pp. 776-780. Coconut Creek (Florida), ISSN 0749-0208.

Lumbroso, D. M., Suckall, N. R., Nicholls, R. J., White, K. D., 2017. Enhancing resilience to coastal flooding from severe storms in the USA: international lessons. NHESS, 17(8), 1357.

Lyard, F., Lefevre, F., Letellier, T., Francis O., 2006. Modelling the global ocean tides: modern insights from FES2004 Ocean Dyn., 56, pp. 394-415.

Nicolae Lerma, A., Bulteau, T., Elineau, S., Paris, F., Durand, P., Anselme, B., Pedreros, R., 2018. High-resolution marine flood modelling coupling overflow and overtopping processes: framing the hazard based on historical and statistical approaches. Nat. Hazards Earth Syst. Sci., 18, 207-229.

Rohmer, J., Idier, D., Paris, F., Pedreros, R., Louisor, J., 2018. Casting light on forcing and breaching scenarios that lead to marine inundation: Combining numerical simulations with a random-forest classification approach, Environmental Modelling & Software, Volume 104, Pages 64-80.

Rohmer, J., Lecacheux, S., Pedreros, R., Idier, D., Bonnardot, F., 2019. Early warning system for cyclone-induced wave overtopping aided by a suite of random forest approaches. In: SimHydro, 12-14 June 2019, Sophia Antipolis, France.

Sauvagnargues S. et Ayral P-A. (2015), Les outils et méthodes de la gestion de crise « inondation » : la protection des personnes, des biens et de l'environnement. Géologues, 2015-184, pp. 62-67.

Sauvagnargues S., Ayral P.-A., Tena-Chollet F., Wassner T., Frealle N., 2017. Impact des Evènements Météorologiques Dangereux sur la gestion de crise des communes : application aux PCS des communes de l'île de la Réunion. *Geo-Eco-Trop,* Tome 3, pp. 437-454.

Sauvagnargues, S., Ayral, P.A., Tena-Chollet, F., Fréalle, N., Wassner, T., 2018. Méthodologie d'appui aux communes pour la gestion de crise des inondations fluviales et côtières : évaluation objective des plans communaux de sauvegarde (PCS) et organisation d'exercices de gestion de crise. La Houille Blanche.

Suzuki, T., Verwaest, T., Veale, W., Trouw, K., Zijlema, M., 2012. A numerical study on the effect of beach nourishment on wave overtopping in shallow foreshores. Coastal Engineering Proceedings 1, 50.

Taylor, A.A., and Glahn, B., 2008. Probabilistic guidance for hurricane storm surge. In: 19th Conference on Probability and Statistics. Pp. 7-4.

Tolman, 2014: User manual and system documentation of WAVEWATCH- III version 4.18. NOAA/NWS/NCEP/MMABTech.

Goldstein, A., Kapelner, A., Bleich, J., Pitkin, E., 2015. Peeking inside the black box: Visualizing statistical learning with plots of individual conditional expectation. Journal of Computational and Graphical Statistics, 24(1), 44-65.

Wei, P., Lu, Z., Song, J., 2015. Variable importance analysis: a comprehensive review. Reliab. Eng. Syst. Saf. 142, 399e432

Zijlema, M., Stelling, G.S., Smit, P.B., 2011. SWASH: an operational public domain code for simulating wave fields and rapidly varied flows in coastal waters, Coastal Engineering 58 992–1012.