Use of high water marks and eyewitness accounts to delineate flooded coastal areas: The case of Storm Johanna (10 March 2008) in Brittany, France

Jean-Marie Cariolet*

Gêomer — UMR 6554 CNRS LETG (Université de Bretagne Occidentale), Institut Universitaire Européen de la Mer, Technopôle Brest — Iroise, Place Nicolas Copernic, 29285 Plouzané, France

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A B S T R A C T

Mapping flooded coastal areas can be carried out using different methods and can promote a better understanding and management of coastal flood risks. The delineation of the coastal areas in western Brittany inundated during a storm that came through on 10 March 2008 was determined based on eyewitness accounts and physical marks noted in situ. Using this methodology, 25 sites were mapped, representing an overall flooded area of more than 30 ha. The delineation of the flooded areas was compared with the official French (PPR-SM) flood zones, revealing some discrepancies. Finally, two case studies illustrate how coastal flood mapping can be useful for validating hydrodynamic models.

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1. Introduction

There are many methods for mapping areas that are occasionally subject to coastal flooding. Large surfaces of flooded areas can be mapped using satellite images [1,2]. Based on a resolution of several tens of meters, this technique can only be used when flooding affects a large surface area. For example, satellite image mapping is not appropriate for the coast of Brittany where most low-lying coastal areas comprise relatively small land surfaces. An alternative method involves aerial surveys of flooded areas during inundation, which generally occurs during high tide in a macrotidal environment [3]. However, this technique is entirely dependent on weather conditions that are rarely clement during coastal flood events.

When neither of these two methods can be used, the remaining solution is to collect evidence in the field. This method has been effectively used after tsunami and hurricane events — in particular Hurricane Katrina — and provides useful information. For example, some studies compile eyewitness accounts to delineate the areas that had been flooded [4–7]. Others use in situ physical marks or markers to determine horizontal and vertical high water levels. Storm deposits and visible water marks left on the walls of buildings are excellent markers of the elevation of flood waters [5,6,8–10]. Identifying damage to vegetation (injury due to salt water and broken branches on trees and shrubs) can also help delineate areas that were inundated for several hours [5–11].

When these markers cannot be used (or are no longer visible), sediment deposits can provide other clues. The analysis of sediment deposits from tsunamis or storm surge is based on grain sorting and many studies have demonstrated the link between sorting and the limits of the flooded area. A horizontal gradient can be distinguished by a change in grain size from coarse to fine as the limits of the inundated areas are reached; likewise, vertical limits can be determined from the sediment layer deposited by swash and the sediment layer deposited by backwash [4,7,11–16]. However, the upper limits of sediment deposits are often lower than the actual highest water level reached by run-up, because backwash tends to erase them. Sediment deposits thus only rarely correspond to the limits of the flooded area, and this method of delineation may thereby underestimate the extent of flooding [11].

Mapping flooded areas is useful for several reasons. First, many authors stress the fact that information on the extent of flooding must be collected quickly to assess damage, to assist authorities and insurance companies in determining damage and to produce flood risk maps [2,6,14]. Second, the use of geographic information systems (GIS) makes it possible to compare flooded areas with official flood zones — created by regulations such the French Coastal Flood Risk Prevention Plans (Plans de Prévention des Risques-Submersion Marine, PPR-SM) in France or the Federal Emergency Management Agency (FEMA) in the United States—to estimate their veracity [8,17]. Third, mapping flood data can help validate hydrodynamic models [10], Fletcher et al. [8] and Tsuji et al. [5] have used mapping to validate their estimates of extreme water levels obtained using numerical approaches. Other studies have mapped flood water marks to validate wave overtopping models that simulate the extent of flood zones [3,18,19].

* Tel.: +33 664 03 12 91; fax: +33 02 98 49 87 03.
E-mail address: jean-marie.cariolet@univ-brest.fr.
On 10 March 2008, a storm hit the northwestern coast of France during a spring tide, causing coastal flooding in many areas. The extreme water levels observed on that day were due to the rare combination of several marine weather phenomena: storm surge, rough seas and spring tide. Accordingly, flooding on Brittany’s macro- and megatidal coasts took place during two successive high tides. During the morning high tide, when the storm eye was located near Ireland, a strong southwesterly flow caused many floods on the southern coast of Brittany. During the evening high tide, the storm eye was located on the eastern coast of the United Kingdom, causing a strong northwesterly flow and flooding occurred mainly on the northern coast of Brittany. The wind and waves observed during this storm have a two-year return period. For the observed tides, the return periods range from 2 to 100 years [20].

This study presents the method that was employed to delineate the areas that underwent coastal flooding in Brittany on 10 March 2008. The results are then illustrated by three specific examples that demonstrate the usefulness of mapping low-lying coastal areas that were flooded during this storm event.

2. Materials and methods

In macrotidal and megatidal environments, coastal flooding generally only lasts several hours, and usually occurs during high tide. No aerial surveys could be undertaken on 10 or 11 March 2008 in Brittany. Thus, any evidence that could help to delineate areas that were flooded during the storm was collected directly in the field. This evidence included in situ physical marks (wrack lines, ...

Fig. 1. Physical marks used in this study. A. Wrack line, Tredrez-Locquémeau (Côtes-d’Armor). B. Water mark on a wall, Tredrez-Locquémeau.

Fig. 2. Diagram summarizing the different layers incorporated in the GIS for mapping the flooded coastal areas.
high water marks on walls) or was based on eyewitness accounts from people present during the flood event (Fig. 1).

On 11 March 2008, an inventory of all sites that were flooded in Brittany was drawn up based on local newspaper articles and telephone calls to town halls to confirm whether or not town had been flooded. Since the longer the time after a flood, the more any evidence is attenuated (e.g. physical marks erased and eyewitness accounts more vague), the affected coastal municipalities were visited as quickly as possible.

2.1. Collecting data in the field

Field investigations were based on a series of informal interviews with local residents as well as on an inventory of the physical
marks that indicated the (vertical and horizontal) limits of flooding (Fig. 2). During each informal interview, the following information was recorded: street address (house number and street name) to map the interview, the degree of flooding, the time and duration of flooding, the high water level, the direction of current flow, and where the seawater came from. Each eyewitness was also asked to indicate the limits of the flooded area. The identified limits of the flooded areas were mapped using a GPS or by noting the address of the residence closest to the indicated limit.

Each interview was assigned a code (interview1, interview2, etc.) and recorded both in a field notebook and on a map. The information provided in each interview was compared with neighbors’ answers and vertical marks to confirm (or invalidate) the previous interview. Many eyewitnesses—who had filed insurance claims for damages incurred—often exaggerated the facts. Untrue accounts were easy to identify and were eliminated from the database. Ultimately, all interviews, which were mapped using their street address, contributed to a grid of points of gathered data; these data points were then ‘interpolated’ to delineate the flooded area.

Each piece of evidence/physical mark (e.g. wrack lines and water marks on walls) was also coded and photographed.

Fig. 5. Spatial distribution of flooded coastal area at Beniguet Island (Finistère).

Fig. 6. Location of the built-up coastal areas that were flooded during Storm Johanna in Brittany, France on 10 March 2008.
Whenever possible, these marks were mapped with a differential GPS (DGPS) to the nearest centimeter to determine the elevation\(^1\) of the flood water levels. Regarding swash marks, their elevation sometimes indicated the maximum level of run-up. This was equal to the maximum run-up \(R_{\text{max}}\) reached during inundation. This information is very useful because it helps to validate the theoretical and mathematical approaches that are often used to calculate extreme water levels. These levels also delineate flood-prone zones (PPR-SM zoning) and define crest levels for coastal structures (breakwaters, etc.). The data collected at Tredrez-Locquémeau (Côtes-d’Armor département) presented in the Results (Section 3.2) will address this point in particular.

### 2.2. Incorporation of data into a GIS database

All the information gathered in the field was then incorporated into a GIS database, using ArcGIS 9.2 software. Each interview was mapped based on the street address of where the interview took place. The delineation of the flooded areas was deduced from the grid of interviews and physical marks. Where topographic surveys were conducted, delineations were obtained from the contour line determined from the height of debris lines, using Surfer 8 software (Fig. 2). The flooded areas were digitalized on the French National Geographic Institute (Institut Géographique National, IGN) 2005 orthophotographs (BD ORHTO\(^\circ\)) or on IGN SCAN25 digital maps by overlaying surface elements (polygons). Surface areas were calculated from these polygons. The swash marks—which delineate the area that was flooded—measured using DGPS were incorporated into the GIS database using Surfer 8 software. They were represented by line elements and were used to delineate the flooded areas in certain areas more precisely (Fig. 2). Each field measurement of alleged water levels was symbolized by a point element (information related to the point, such as water level, were incorporated as point attributes). Finally, wave overtopping and/or overflow areas were represented by a line element (Fig. 2).

### 3. Results

Extracts from the GIS database illustrate how the interviews (symbolized by points on the maps) and physical marks made it possible to map the areas that were flooded (Figs. 3–5). At Gâvres (Morbihan département), a highly built-up site and where no horizontal marks could be detected, interviews and vertical marks were...
Fig. 8. Delineation of the areas flooded on 10 March 2008 and the official PPR-SM zones for the town of Ile Tudy (Finistère) (source: Baillet [22]).

Fig. 9. Port of Tredrez-Locquémeau on 11 March 2008 (photo: Joel Le Jeune). The shingle barrier that protects the low-lying area located landward was leveled and pushed landward by rollover. By comparing aerial IGN orthophotographs from 2005 and DGPS coordinates, the barrier migrated landward by an estimated 9 m.
were the main indications that could be used to delineate the flooded area (Fig. 3). At Tredrez-Locquemeau (Côtes-d’Armor) and on Beniguet Island (Finistère département), where the degree of human influence is low or practically nil, swash marks were recorded with a DGPS, and then used to precisely map flooded surfaces (Figs. 4 and 5).

The sites that were inundated during the morning high tide on 10 March 2008 were mainly located on the southern coast of Brittany and oriented in a south-southeastern direction (Fig. 6). These low-lying areas, whose shorelines directly face onshore winds, experienced many overflows after the active cold front came through [20]. During the evening high tide, after surging seas developed in the Atlantic Ocean, the coastlines of Finistère and the Tregor region (Côtes-d’Armor) were the most affected (Fig. 6). Overall, nearly 25 cases of flooding in built-up areas were inventoried in Brittany on 10 March 2008 alone.

Based on the constituted GIS database, the total surface of built-up areas that were flooded on 10 March 2008 was determined to be equal to 24.4 ha (Fig. 6). This value probably underestimates the surface actually flooded because many sites were less drastically flooded and could not be mapped. Inundated surfaces covered an average of 1.1 ha. The largest flooded area was located at Gâvres (Morbihan) where nearly 6.7 ha were submerged (Fig. 3).

As mentioned above, these results are useful in more than one aspect and can be utilized in different ways. The following three cases illustrate how mapping areas flooded on 10 March 2008 can be useful for better management and understanding of coastal flooding.

3.1. Case study 1: comparison of flooded areas with regulatory seawater flood zones (Finistère)

The French Coastal Flood Risk Prevention Plans (Plans de Prévention des Risques de Submersion Marine - PPR-SM) were instituted as Law no. 95–101 of 2 February 1995 (also known as the Barnier Law), and can be considered analogous to actions undertaken under the auspices of FEMA. The PPR-SM regulates land use according to the flood risk of the land area in question. The objective of the PPR-SM is to guarantee human safety, reduce the vulnerability of property and activities in flood-prone areas and limit insurance claims in case of a flood event [21].

In Finistère, 22 municipalities have ratified a PPR-SM flood zone. These zones are based on 100-year return extreme water levels calculated by the French Naval Hydrographic and Oceanographic Service (Service Hydrographique et Océanographique de la Marine, SHOM). Since the storm event on 10 March 2008 can be considered as a reference for coastal flooding, the objective was to compare official PPR-SM flood zones with areas that were actually flooded on 10 March 2008.

3.1.1. Methods

The GIS layer representing the regulatory flood zones laid out in the PPR-SM (Source: DDEA 29) was superimposed on the GIS layer representing areas that were flooded on 10 March 2008 in Finistère. This approach identified areas that were inundated during the storm and classified as part of the official PPR-SM flood zone.

3.1.2. Results

Results show that for the Finistère département, only 2.7% of areas flooded on 10 March 2008 were located in an official PPR-SM flood zone. Two observations can be drawn from this comparison. First, many municipalities that were flooded in March 2008 do not have designated flood-prone zones. These municipalities include Sein Island, Ushant Island, Molène Island and also Audierne, Camaret-sur-Mer and Douarnenez. Second, of the municipalities that have defined flood zones and that were flooded on 10 March 2008, the flooded areas did not correspond to the official PPR-SM flood zones. The examples of the towns of Penmarc’h and Ile Tudy (southern Finistère) are particularly instructive. At Penmarc’h, the Saint-Guénolé port and the low-lying coastal area located landward were inundated on the evening of 10 March 2008 (Fig. 7). This same coastline had already been flooded on 13 December 1978 (source: Le Télégramme, regional newspaper, 14 December 1978). However, none of the official PPR-SM flood zones (red, blue and green zones) ratified in December 1999 include the port (Fig. 7).

At Ile Tudy, the area that underwent flooding on 10 March 2008 is located at the tip of the peninsula (Fig. 8). This area has already been flooded several times, notably on 27 October 2004 (source: Le Télégramme, 28 October 2004). Nevertheless, the official PPR-SM flood zone ratified in June 1997 does not include the tip of the peninsula (Fig. 8).

These comparisons show that the official PPR-SM flood zones that were defined during 1997–2007 are inconsistent with areas that were actually flooded during the 10 March 2008 storm. Nevertheless, these results should be interpreted with caution because they are based on only one storm event, which was exceptional in character [20].

3.2. Case study 2: using swash marks to validate estimates of extreme water levels

Many studies concur that the elevation of the high water mark corresponds to the highest level reached by swash and thereby indicates wave run-up, theoretically occurring during high tide [23]. This can be expressed by the following equation:

\[ \text{Elevation}_{\text{swash mark}} = \text{Elevation}_{\text{observed high tide}} + R_{\text{max}}^{T} \]  

where \( R_{\text{max}}^{T} \) corresponds to the highest level of run-up reached at a given location on the beach.

Nott and Hubbert [10] thus compare elevation of storm deposits with extreme water levels estimated from storm-surge models. The high water deposits left by the 10 March 2008 storm were used to
validate the estimates of extreme water levels calculated from numerical formulas. Taking the example of Tredrez-Locquémeau (Côtes-d’Armor), this town was suddenly flooded on 10 March 2008 around 19:00 UTC (Fig. 4) by waves that flooded the shingle barrier which protects the low-lying coastal area located landward (Fig. 9). Storm deposits indicated the highest level reached by swash (Figs. 1, 9 and 10). This physical mark, recorded using DGPS, presents the height of offshore waves, and \( \xi_0 \) is the Iribarren number [28], or

\[
\xi_0 = \tan \beta/(H_o/L_o)^{1/2}
\]  

(6)

where \( L_o \) is the offshore wavelength (1.561 T²).

3.2.2. Results

On 10 March 2008 at 19:00 UTC, i.e. during the evening high tide, the Lannion-Servel weather station recorded a pressure of 986.8 hPa and a westerly wind (direction 270°) of 15 m/s. At the same point in time, the storm eye was located at 450 km from Tredrez-Locquémeau.

Calculated from mathematical models (equations (2)–(4)), storm surges reached 0.74 m during the evening high tide, or 0.26 m (elevation due to the inverse barometer effect) plus 0.48 m (elevation due to wind set-up). The storm surge recorded by the Roscoff tide gauge at the same point in time was 0.29 m, or 0.45 m lower. The calculation of maximum run-up at 19:00 UTC was based on simulated wave data⁴ (\( H_{max} = 10.2 \) m and \( T_{pic} = 16 \) s) and morphological data (beach slope = 0.026). The maximum run-up reached at 19:00 UTC was estimated at 1.78 m.

Adding the height of high tide predicted at 19:00 UTC (4.356 m), the calculated value of storm surge (0.74 m) and the maximal run-up value (1.78 m) give an estimated water level of 6.876 m. This value roughly corresponds to the elevation of the storm deposits that had a mean elevation of 6.5 m and a maximum elevation of

where \( dA \) represents the increase in water level due to a drop in atmospheric pressure - a 1 hPa decrease in pressure leads to a 1 cm increase in water level - and \( d\xi \) represents the water level generated by wind set-up. Wind set-up can be estimated using the expression developed by Bowden [26]:

\[
d\xi = (\xi_0\rho g h) \cdot d_k
\]  

(3)

where, \( g \) = acceleration due to gravity (9.81 m/s²), \( \rho \) = density of seawater (water at 12 °C = 1026 kg/m³), \( h \) = depth of wave-base level, calculated from the equation \( h = 2.28 H_o 68.5(H_o^2/gT_e^2) \) where \( H_o \) and \( T_e \) are the height and the associated period, respectively, of waves that exceed 12 h in one year, and \( d_k \) = fetch of the center of the depression to the coast (m); and

\[
\tau_s = \rho_aC_D W^2
\]  

(4)

where, \( \rho_a \) = density of air (1.21 kg/m³), \( W \) = wind velocity (m/s) \( 10^{-3} \), \( C_D \) = drag coefficient.

The meteorological data necessary for these formulas come from the data recorded at the Météo-France weather station at Lannion-Servel, located 8 km to the northeast of Tredrez-Locquémeau.

Maximal wave run-up was estimated from the equation developed by Holman [27]:

\[
R_{max}^R = 1.07H_o\xi_0
\]  

(5)

where \( R_{max}^R \) represents the value of maximum run-up, \( H_o \) represents the height of offshore waves, and \( \xi_0 \) is the Iribarren number [28], or

\[
\xi_0 = \tan \beta/(H_o/L_o)^{1/2}
\]  

The same event at Tredrez-Locquémeau developed on 10 March 2008 around 19:00 UTC (Fig. 4) by waves that flooded the shingle barrier which protects the low-lying coastal area located landward (Fig. 9). Storm deposits indicated the highest level reached by swash (Figs. 1, 9 and 10). This physical mark, recorded using DGPS, presents the height of offshore waves, and \( \xi_0 \) is the Iribarren number [28], or

\[
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\]  

(6)

where \( L_o \) is the offshore wavelength (1.561 T²).

3.2.1. Methods

The extreme water level reached during the 10 March 2008 event at Tredrez-Locquémeau can be numerically calculated using equation (1). To obtain the elevation of storm surge during high tide at 19:00 UTC, values were taken from the tide gauge located at Roscoff, the closest representative tide gauge, located 31 km to the west. However, Tredrez-Locquémeau’s coastline directly faces any onshore winds coming from the west, suggesting that the storm surge was higher here than at the port of Roscoff, which is oriented northward. Therefore, storm surge was estimated using the following equation:

\[
S = dA + d\xi
\]  

(2)

where \( dA \) represents the increase in water level due to a drop in atmospheric pressure - a 1 hPa decrease in pressure leads to a 1 cm increase in water level - and \( d\xi \) represents the water level generated by wind set-up. Wind set-up can be estimated using the expression developed by Bowden [26]:

\[
d\xi = (\xi_0\rho g h) \cdot d_k
\]  

(3)

where, \( g \) = acceleration due to gravity (9.81 m/s²), \( \rho \) = density of seawater (water at 12 °C = 1026 kg/m³), \( h \) = depth of wave-base level, calculated from the equation \( h = 2.28 H_o 68.5(H_o^2/gT_e^2) \) where \( H_o \) and \( T_e \) are the height and the associated period, respectively, of waves that exceed 12 h in one year, and \( d_k \) = fetch of the center of the depression to the coast (m); and

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\]  

(4)

where, \( \rho_a \) = density of air (1.21 kg/m³), \( W \) = wind velocity (m/s) \( 10^{-3} \), \( C_D \) = drag coefficient.

The meteorological data necessary for these formulas come from the data recorded at the Météo-France weather station at Lannion-Servel, located 8 km to the northwest of Tredrez-Locquémeau.

Maximal wave run-up was estimated from the equation developed by Holman [27]:

\[
R_{max}^R = 1.07H_o\xi_0
\]  

(5)

where \( R_{max}^R \) represents the value of maximum run-up, \( H_o \) represents the height of offshore waves, and \( \xi_0 \) is the Iribarren number [28], or

\[
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Calculated from mathematical models (equations (2)–(4)), storm surges reached 0.74 m during the evening high tide, or 0.26 m (elevation due to the inverse barometer effect) plus 0.48 m (elevation due to wind set-up). The storm surge recorded by the Roscoff tide gauge at the same point in time was 0.29 m, or 0.45 m lower. The calculation of maximum run-up at 19:00 UTC was based on simulated wave data⁴ (\( H_{max} = 10.2 \) m and \( T_{pic} = 16 \) s) and morphological data (beach slope = 0.026). The maximum run-up reached at 19:00 UTC was estimated at 1.78 m.

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⁴ Swell data obtained by simulation using the WAVEWATCH III™ wave model (SHOM).
7 m. This shows the usefulness of an empirical field approach for calculating extreme water levels.

3.3. Case study 3: using swash marks to calculate incoming water volumes

The eastern part of Beniguet Island, located in the Molène archipelago (Finistère), consists in a gravel barrier surrounding low-lying areas inland, called the „Tahiti” barrier. This part of the island was particularly invaded by the sea on 10 March 2008 (Fig. 5). Seawater entered through two breaches created during Winter 1989–1990 (Fig. 11). Many pebbles were dumped on the other side of the Tahiti barrier at the northeastern part of the island and prove that seawater overtopped the barrier, flooding one of the two affected low-lying areas.

As the island is classified as an integral nature reserve, swash marks remained intact after the 10 March 2008 storm. This site, free from any human-related disturbances, was an exceptional study site for studying a coastal flood event.

3.3.1. Methods

3.3.1.1. Estimation of incoming water volumes in the low-lying areas based on measurements of swash marks and topographical surveys.

First, swash marks were surveyed using DGPS. The data were linked to the French geodetic system and to the Lambert II projection system through an IGN terminal located on the island.\(^5\) Swash marks could therefore be georeferenced to determine their elevation and determine the limits of the area that was flooded on 10 March 2008. The whole flooded area, the shingle barriers, the two breaches and the foreshore were thus surveyed. More than 5300 points were recorded during two visits to the island (20–21 May 2008 and 24 June 2008). A digital elevation model (DEM) was calculated based on the surveyed points, according to a 50 × 50 cm grid (Fig. 12). The volume of water that flooded the island during the storm was then estimated, assuming that the substrate is impermeable. Using the reference elevation, data were recorded regarding the morphological characteristics of the flooded area, such as the altitude of the two breaches and the shingle barrier which waves overtopped.

3.3.1.2. Calculation of the volume of water that overtopped natural island structures.

The overtopping discharge rates were calculated for Breaches 1 and 2 and the Tahiti barrier using the equation developed by Van der Meer and Janssen [30] and widely used in civil engineering [19,31]:

\[
\frac{q_w}{\sqrt{gH^3}} = 0.06 \frac{\xi_{op}}{\tan \beta} \exp \left( -5.2 \frac{R_c}{H_b} \frac{1}{\xi_{op}} \frac{1}{\gamma_r \gamma_b \gamma_h \gamma_i} \right) \text{ for } \xi_{op} < 2
\]

where, \(q_w\) = mean overtopping discharge rate (m\(^3\)/s/m), \(\xi_{op}\) = Iribarren number or surf similarity parameter [28], see equation (6), \(\tan \beta\) = beach slope, \(R_c\) = height of coast at the point of overtopping - observed tide, \(H_b\) = significant wave height, \(\gamma_r \gamma_b \gamma_h \gamma_i\) = reduction factors for slope roughness, presence (or absence) of a berm, shallow water and angle of wave approach, \(g\) = acceleration due to gravity.

Data on storm waves were obtained from measurements taken by the (directional Datawell) wave gauge located near Pierres Noires, 5 km southwest of Beniguet Island. The tide data come from the tide gauge at Le Conquet located 5 km east of Beniguet Island.

To obtain the total volume of water that overtopped the breaches and the Tahiti barrier, the mean discharge rates, expressed as m\(^3\)/s/m, were multiplied by the length of the coastline overtopped and the number of waves counted during the period considered (period in seconds divided by the wave period \(T_{pic}\), e.g. 30 min with \(T_{pic} = 15\) s, or 1600 s/15 s = 120 waves).
3.3.2. Results

3.3.2.1. Estimation of the volume of overtopping water and morphological characteristics of the areas that were overtopped. Both breaches have identical morphology and the same elevation: 4.7 m (8.2 m on marine charts). For comparison, the highest astronomical tides reach 4.24 m (7.74 m on marine charts) in this part of the Molène archipelago. The mean elevation of the swash mark deposited by the storm tide in the trough of the low-lying area (Loc’h, Breach 1) was 4.7 m. It can be thus assumed that the trough was “filled” up to the rim. Most of the water entered by the breach, even though the projection of pebbles behind the Tahiti barrier proves that waves also overtopped the opposite side of the breach (Fig. 8). The calculated water discharge, assuming that the ground is impermeable, was 54 791 m$^3$ (Table 1). However, the sandy substrate is porous, suggesting that the volume of discharged water was greater.

Regarding the mean elevation of swash marks reached 3.7 m. The 19 073 m$^3$ of water entered the breach (Table 1). Here, water only entered through the breach, which may explain the lower water volume compared to Breach 1.

3.3.2.2. Calculation of the volume of overtopping waves. Mean overtopping discharge was calculated for the three areas that were overtopped and whose morphological characteristics are compiled in Table 1. The results show that Low-lying area 1 (Loc’h) was flooded by overtopping at breach 1 in the morning and in the evening. The “Tahiti” barrier was overtopped only in the evening. Low-lying area 2 was flooded by overtopping at Breach 2 in the morning and in the evening (Fig. 13). Calculated overtopping volumes matched relatively well those measured in the field (Table 2).

4. Discussion

While the combined use of eyewitness accounts, high water marks and topographic surveys for delineating flood zones is not new in coastal flooding studies [4–10], this is the first study to employ this [three-pronged] approach in a macro- and megatidal environment, where inundations are very short-lived. The data gathered in this study and specific analysis of the study region thus provide valuable information for coastal flood management in Brittany. The quality control of the verbal interviews constitutes one limitation of the data utilized in this study; however, false accounts could easily be identified by cross-checking with neighboring residents’ accounts and vertical marks.

Fletcher et al. [8] and Dobosiewicz [17] compared official zones defined as flood-prone in the United States by FEMA with areas that were actually flooded during hurricanes. These studies assessed the pertinence of the official flood zones. In the present study, mapping helped to show that there were numerous inconsistencies between official PPR-SM flood zones and zones that were actually flooded. In Finistère, many municipalities that were flooded such as Sein Island, Audierne and Dournenez have not defined official flood zones. Moreover, in municipalities where flood zones have been defined, zones that were flooded did not necessarily correspond to those that are indicated on official flood maps. The comparison between 100-year return flood zone and Storm Johann-ﬂooded areas is limited because the storm-surge response varied, reaching from 2- to 100-year return surge levels depending on the location. Nevertheless, coastal flooding with a two-year return surge level in an area that is not even referenced as a 100-year return flood zone shows that other parameters, such as wave run-up, have to be taken into account to estimate extreme water levels and thus PPR-SM flood zones.

The present study highlights the importance of obtaining and archiving spatial data that indicate the actual extent of flooding. At the request of government authorities, municipalities declare damage incurred within municipal limits to file insurance claims and obtain monetary compensation. Most declarations of natural disasters are not accompanied by any georeferenced data. Setting up a GIS database would serve as a “risk memory” and better localize the areas that are at flood risk. This type of work has been carried out in the United States by FEMA [9,32,33]. In France, mapping flooded areas may, for example, supplement and contribute to the French national natural disaster database (known as the CatNat/GASPAR database) by adding a fine-scaled spatial approach. This database has some shortcomings [34] and mapping would help enhance the information contained in it.

Work carried out in Tredrez-Locquémeau shows the importance of revising theoretical estimates of extreme water levels in France. The approach used here, which takes the effect of waves into account in estimating water levels on the coast (run-up), proved to be more accurate than the method used by SHOM [24], which only considers storm surge and underestimates extreme water levels (Fig. 14). Many PPR-SM flood zones have been delineated based on 100-year return levels calculated by SHOM, such as the PPR-SM

Table 1

<table>
<thead>
<tr>
<th>Overtopped areas</th>
<th>Length of overtopped coastline (m)</th>
<th>Elevation at the entrance of the breach (m)</th>
<th>Beach slope (tan $\beta$)</th>
<th>Affected Low-lying area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breach 1</td>
<td>92</td>
<td>4.7 (NGF)</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>Breach 2</td>
<td>104</td>
<td>4.7 (NGF)</td>
<td>0.081</td>
<td>2</td>
</tr>
<tr>
<td>Tahiti barrier</td>
<td>90</td>
<td>6.73 (NGF)</td>
<td>0.15</td>
<td>1</td>
</tr>
<tr>
<td>Low-lying area</td>
<td>Elevation of swash mark</td>
<td>Volume of incoming water on 10 March 2008</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-lying area 1 (Loc’h)</td>
<td>4.7 (NGF)</td>
<td>54 791 m$^3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-lying area 2</td>
<td>3.7 (NGF)</td>
<td>19 073 m$^3$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Affected Low-lying area</th>
<th>Observed volume (m$^3$)</th>
<th>Calculated volume (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-lying area 1 (north)</td>
<td>54 791 m$^3$</td>
<td>50 774 m$^3$</td>
</tr>
<tr>
<td>Low-lying area 2 (south)</td>
<td>19 073 m$^3$</td>
<td>22 155 m$^3$</td>
</tr>
</tbody>
</table>

Fig. 13. Average wave-only overtopping discharge rate calculated for the two breaches and the Tahiti barrier and total incoming water volume on 10 March 2008.
flood zones in northern Finistère and in the town of Guisseny [25]. The official PPR-SM flood zones are inaccurate, because the reference water level used does not account for rough seas and thereby underestimates real water levels. Accordingly, more and more studies favor an approach that integrates the effects of both set-up and run-up [19,25,35–37]. In this study, the swash marks were used to validate estimates of extreme water levels at only one location. Most of the swash marks surveyed after this storm were located in low-lying areas and cannot be used to determine run-up elevation. Only at Tredrez-Locquémeau was a swash mark located above a coastal defense structure, and actually attests to run-up elevation.

Finally, the study conducted on Beniguet Island shows that the wave overtopping model, based on Van der Meer and Janssen [30], used for designing coastal structures such as breakwaters or jetties, is also useful for natural barriers such as dunes and shingle barriers.

5. Conclusion

This paper presented a method used for mapping seawater flooded areas during Storm Johanna that hit Brittany on 10 March 2008. The combined use of eyewitness accounts and physical marks led to a relatively precise delineation of flooded areas that was sometimes further improved with DGPS surveys. This method can be applied rather well to a large range of environments, whatever their degree of human impact. In built-up areas, field work should include interviews such as at Gâvres (Fig. 3), although in pristine areas, such as on Beniguet Island (Fig. 5), only physical markers can be used. This field approach circumvents dependence on image data—which can sometimes be difficult to obtain—or on assertions made by authorities in municipalities that have no or little georeferenced data.

The compilation of data in a GIS optimizes the usefulness of spatial data. It was therefore possible to pinpoint some inconsistencies between PPR-SM flood zones and areas that were actually flooded in March 2008 in Finistère. Mapping was also useful for validating hydrodynamic models, in particular those that have been developed to estimate extreme water levels and the volume of overtopping water.

Overall, mapping can be a valuable tool for managing seawater flood risks in Brittany. It may also help government authorities to reassess the delineation of future PPR-SM flood zones in some coastal towns at risk.

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References

[10] Nott J, Hubbert G. Comparisons between topographically surveyed debris lines and modelled inundation levels from severe tropical cyclone Vance and