Chapter 10
Quantification of Historical Skew Surges: Challenges and Methods

Emmanuelle Athimon, Nathalie Giloy, Thierry Sauzeau, Marc Andreevsky, and Roberto Frau

Abstract The use of historical sources and data to improve knowledge of past extreme events is no longer to be demonstrated. Old quantitative and qualitative data on water levels available in non-digitized tidal charts, tide gauge records, newspapers, city council registers, engineers' reports, etc. can be used to reconstruct water levels and skew surges that occurred during a storm. Data from primary and/or secondary historical sources require a historical critical approach. This paper presents an interdisciplinary study that required a combined work between historians, geographers, geologists and engineers. In this study, nine different variables that can lead to uncertainties on the quantification of historical skew surges have been identified, such as tidal predictions, chart datum references or the reliability of the historical data. Starting from the historical critical method developed by historians over decades, we propose a three-step method to assess the quality of historical documents and define their level of reliability. The method is applied to two case studies: the storm of 16th November 1940 and the storm of 15–16th February 1941. Interesting results are provided and the study shows that by paying attention to the potential causes of uncertainties, by ensuring the reliability of historical sources and data through the

E. Athimon (✉)
Laboratoire d'Hydraulique Saint-Venant-Ecole des Ponts ParisTech, 6 quai Watier, 78400 Chatou, France
e-mail: emmanuelle.athimon@enpc.fr

N. Giloy
Shom-IRSN, (Shom) 13 rue du Chatellier, 29200 Brest, France
e-mail: nathalie.giloy@shom.fr

T. Sauzeau
Centre de Recherche Interdisciplinaire en Histoire, Arts et Musicologie-Université de Poitiers, Hôtel Fumé—8 rue René Descartes, Bâtiment E15, TSA 81118, F-86073 Poitiers, France
e-mail: thierry.sauzeau@univ-poitiers.fr

M. Andreevsky · R. Frau
Electricité De France Recherche and Développement-Laboratoire National d'Hydraulique et Environnement, 6 quai Watier, 78400 Chatou, France
e-mail: marc.andreevsky@edf.fr

R. Frau
e-mail: roberto.frau@edf.fr

P. Gourbesville and G. Caignaert (eds.), *Advances in Hydroinformatics*, Springer Water,
https://doi.org/10.1007/978-981-19-1600-7_10

use of the historical documents quality method, by deepening historical researches and by combining different scientific fields and methods, it is possible to reduce uncertainties and errors when quantifying historical skew surges.

Keywords Storms · Coastal floodings · Historical documents · Uncertainties · Reliability · Extreme events

10.1 Introduction

Over the past 20 years, at least four important storms causing seaflood, major impacts and deaths (Lothar and Martin 1999; Klaus 2009; Xynthia 2010) occurred on the French atlantic coast. These events prove the necessity to implement an efficient historical reconstruction and analysis of past storms, coastal floodings and skew surges over a longer period to better assess the risk associated to these extreme events in France. The use of historical sources and datasets to improve knowledge of past extremes is no longer to be demonstrated [3, 8, 9, 31, 14–15, 18, 21, 23, 28, 29, 32, 42, 45]. Moreover, a full knowledge on extreme events of the past is a key point, as much for scientists, politicians, insurance companies, populations, as for industries.

Two variables commonly used to compare extreme floodings are the maximum water level reached and the skew surge, which is the difference between the maximum observed water level and the maximum predicted water level during one tidal cycle [24]. To estimate return periods, analysis of extremes are performed on skew surges, as they are considered as integrated and unambiguous measure of the storm surge [24]. Still, instrumental records cover only short time periods, which makes the estimation of high return periods quite difficult. In order to extend these instrumental, also called systematic data series, historical information are used [13, 14]. Old quantitative data water levels, such as non-digitized tidal charts or tide gauge records, can be used to reconstruct water levels and skew surges which occurred during a storm. Another useful information are data available in primary and/or secondary historical sources such as post-disaster investigations, chronicles, newspapers, city council registers, engineers' report, water marks. A primary source is a document written by a person who is contemporary with the historical event. It contains first information and descriptions of the author who experiences the events. A secondary source is written by a non-contemporary author who copies or draws inspiration from primary sources. The author, who has not experienced the events of which he/she is speaking, produces a speech about it. These sources and data are mainly qualitative and describe water levels reached regarding to constructions such as bridges, quays, houses or dikes. In order to be used, these kinds of documents require a historical critical approach [26, 34–37]. In fact, neglecting the historical critical method can lead to misunderstandings, errors of interpretation, misleading information and/or false conclusions [4] on the use of historical sources.

The paper, which aims to present an interdisciplinary work that required a significant skill sharing between historians, geographers, geologists and engineers, is structured as follows: first we aim to identify the causes of potential uncertainties on the quantification of historical skew surges, especially in terms of precision and reliability. Secondly we propose a method to evaluate the quality of a historical document. Finally we apply this method to two cases studies, for instance the storms of 16th November 1940 and 15–16th February 1941.

10.2 Data, Methods and Uncertainties on the Computation of Historical Skew Surges

As mentioned beforehand, systematic skew surges are obtained from systematic tide gauge data series [10]. Historical skew surges are values that are obtained either from complementary instrumental measurements or isolated observations or from written qualitative primary and/or secondary historical sources and datasets [13, 14, 48]. The historical data used to compute historical skew surges also includes isolated data points reconstructed during gaps in the systematic measurements, as storms can partially or totally damage the tide gauge resulting in failure in sea level measurements [14] (Fig. 10.1). Giloy et al. [18] propose a method to reconstruct historic water levels using the description of a historical flooding and complementary information such as sketches of docks, sikes or sluice gates. Both systematic and historical skew surges can contain bias and some challenges can lead to over or underestimation of their numerical values.

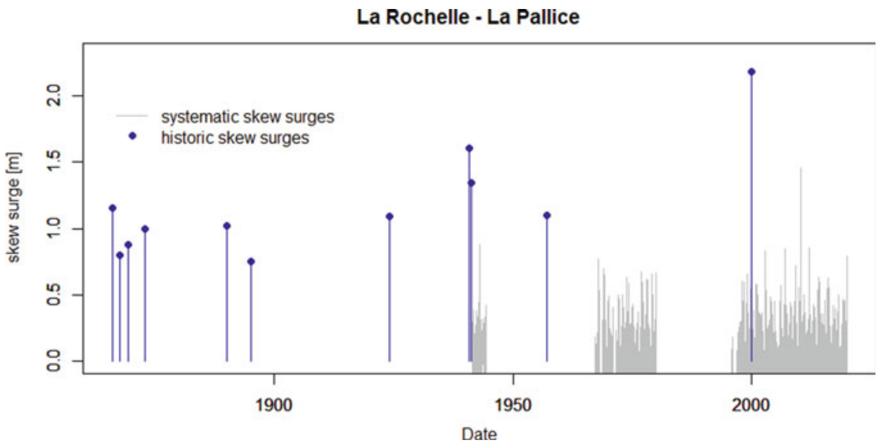


Fig. 10.1 Systematic skew surges at La Rochelle—La Pallice (France) tide gauge and historic skew surges. Historical skew surges of 1866–1872 from [22], of 1890 and 1895 from [15], of 1924 from Departmental archives of Charente-Maritime, 4 S 7678, of 1940-1999 from [6]

10.2.1 Difficulties on the Computation of Historical Skew Surges

In this study, nine different variables that can lead to uncertainties on the quantification of historical skew surges have been identified. These "tricky variables" are currently subject of different scientific researches in order to be able to evaluate and take into account each one of them in our future studies. These nine variables are:

1. Vertical land movements: the causes and the size of the vertical land movements, as well as their spatial extent, vary from place to place in a same area. For example, subsidence was estimated in 1968–1969 at 14 mm.yr^{-1} (millimeter per year) in Venice; beside it is estimated today at 5 mm.yr^{-1} in the south and north of the lagoon of Venice and at 1 or 2 mm.yr^{-1} in the center of the same lagoon [16, pp. 43–44]. The vertical land movement will not be taken into account on the reconstruction of past skew surges of this study. Nevertheless, in order to reduce uncertainties on the reconstruction of past skew surges, the results of geological studies could be integrated in the near future [43, 49, 51];
2. Tidal predictions: in order to estimate a tidal prediction, there is a need for tidal components. These are obtained by harmonic analysis done on sea level observations. Currently, two methods are proposed:

    (a) if tide gauge data contemporary to the event is avaible, this data should be used in a harmonic analysis to estimate contemporary tidal components. These components take into account the contemporary hydrodynamics;
    (b) in absence of contemporary tide gauge data, the tidal components available at the French Hydrographical and Oceanographical Service (Shom) are to be used combined with a correction of mean sea level, to integrate changes in mean sea level. These changes may be integrated by applying a linear trend estimated for each location using available tide gauge data (e.g.: in Cherbourg, changes in sea level is calculated with a time series of sea levels recorded between 1943 to 2018; when in Saint-Malo, it is defined with a time series of sea levels recorded over the period 1986–2018) [50];

At Shom there is an ongoing study which aims to estimate the difference of tidal predictions using these methods presented beforehand [19];

3. Changes in sea level: ignoring changes in sea level when computing astronomical tidal levels can lead to errors in the quantification of historical skew surges. The importance of the error depends on the geographic area and the historical period. If there are no sea level observations for the period of the studied storm, the actual harmonic components must be used to the astronomical tide prediction and changes in sea level must therefore be corrected on this tide prediction [2];
4. Chart Datum References: when using non digitized tide gauge data or complementary information such as sketches of quays or docks, it is important to verify the consistency of the different chart data. Ignoring these can lead to significant

errors when estimating water levels. For example, the position of the tide gauge vertical reference and the chart datum of the site of Saint-Nazaire has changed by 40 cm between the periods 1938–1996 and 1996-present [11] (Fig. 10.2);

5. Bathymetry changes: ignoring the potential variation of the bathymetry over decades or centuries can lead to errors in the reconstruction of past water levels and skew surges. In fact, harbors, sluices, waterway channels, estuarine areas have been often subject to silting up, dredging and anthropogenic developments. Future scientific researches aim to discover ancient maps and plans including bathymetric surveys in historical archives. They could then be cross-checked with historical sources of past storm and coastal floodings and they may be taken into account for the computation of historical skew surges. Further, these ancient bathymetries could be integrated in projects of hydrodynamic modeling;
6. Local hydrodynamic phenomena: tidal predictions will represent the hydrodynamics at the tide gauge locations. Using historic data may leed to water level reconstructions that are not at the same location as the tide gauge, as it has been done for exemple in Dunkirk or La Rochelle [7, 18]. Local phenomena such as amplification or reduction of a water level may occur in harbor areas, waterway channels, rivers. Still these phenomena are difficult to quantify without any further study such as hydrodynamic modeling;
7. The use of anachronistic documents: this can be due to uncomplete historical researches in archives, loss or inexistence of historical sources for the time of interest. It is crucial to be sure of the document's relevance and to contextualize the information it contains. By the way, the risk of over or underestimating for exemple a quay level is still existing and the use of this level could produce afterward some uncertainties on the quantification of historical skew surges [18];
8. Data analysis control: analysing primary and secondary historical documents, critizing and the correctly interpreting their content is crucial. A poor analysis and a little understanding of the content of historical sources can have big consequences [4]. For example, stemmed from the West Indian Spanish word *firacan*, the word "hurricane" was a buzzword from the 18th to the first half

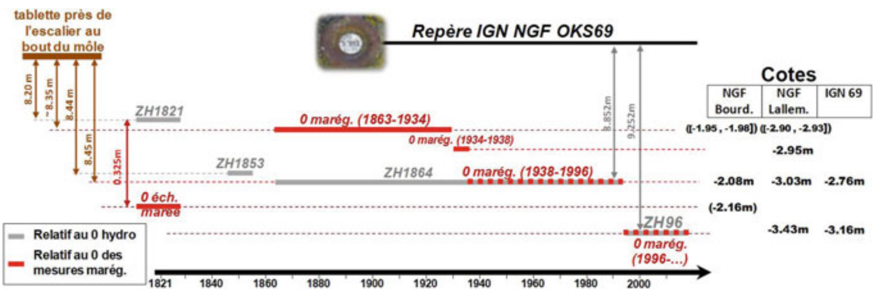


Fig. 10.2 Vertical evolution of the hydrographic and instrumental chart datum references over the time in Saint-Nazaire. From [11], p. 57

of the twentieth century. Written in a historical source, it will not include the meteorological/atmospheric differences in terms of formation between a mid-latitude storm and a hurricane. In addition, it will not even imply a different magnitude or intensity but it will simply be a synonymous of a generic "storm". So, without proper historical critical analysis, a confusion leading to potential errors and false conclusions can arise. Another example of misleading interpretation having consequences for the computation of historical sea level and skew surge is the possible confusion between submersion by wave-overtopping and submersion by sea level;

9. Reliability of the data: what credit can be given to historical sources and the information they contain ? How reliable is a document from the past ? What is the level of confidence of our reconstructed historical skew surges ? This aspect has been identified as one of the biggest variable of uncertainties and potential errors on the computation of historical skew surges.

The point number nine will be handled in this work and a method of evaluating historical sources and data will be presented.

10.2.2 The Historical Documents Quality Method

Studies on the characterization of extremes events need and are keen to use more and more historical sources and data [6, 13, 14, 25, 30, 39, 40]. As suggested earlier, researches do not always pay attention to the method of critical analysis of historical documents developed by historians over decades [26, 34–37]. However, the historical data used to estimate extreme sea levels and quantify historical skew surges must be trustworthy and of good quality. Otherwise, some of the possible risks would obviously be to over or underestimate the levels of reconstructed water levels and skew surges, but also to compute them for storms that did not occur at that time (error of date) or did not impact that specific area (error of location). In this context, a critical analysis and an evaluation of historical documents and data guarantee their reliability, confirm their use for and allow the reconstruction of historical water levels and skew surges.

Both in France and abroad, scientific researchers and research groups on extreme events such as earthquakes, river floods, coastal floodings, avalanches, who use historical documents for their studies, are aware of the importance of working with reliable historical sources and data [5, 17, 20, 33, 38, 47]. Some of them (e.g.: SSHAC, SISFrance, BDHI) have tried to build a quantified rating system in order to define the reliability of historical documents and data they provide [1, 27, 28, 34, 44, 46]. Unfortunately, none of them precisely describes and explains their method and/or has truly implemented a multidisciplinary approach by starting as close as possible to the approach of a historical critical analysis.

The historical critical analysis method works in two stages (Fig. 10.3). At first, historians use the "external criticism" to identify the authenticity of an historical

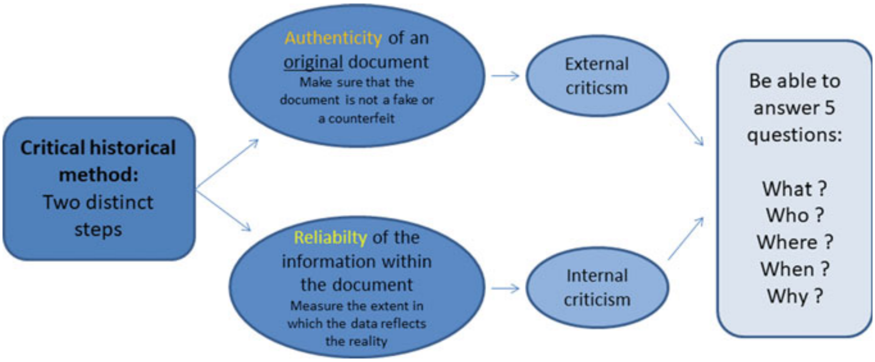


Fig. 10.3 Simplified schematic representation of the historical critical method to analyze historical sources

document. The appearance, the language used, the physical state, the type and nature of the historical source are evaluated to ensure that the source is not falsified or a counterfeit. Secondly, "internal criticism" is used to ensure the reliability of the data contained within the historical source, i.e. analysis of the author, the date, the context, the motivation of the production of the document, etc. This stage aims to establish the extent to which the data reflects the reality of the time.

At the end, the critical analysis of historical sources and their content should answer the five big questions (and their sub-questions):

- What ? (type and nature of the document);
- Who ? (author information);
- Where ? (location of production of the document and site in which the events occurred);
- When ? (date of document production and date of the events);
- Why ? (motivations of the author, reasons for the production of the document).

We start from this historical critical method to develop the method to evaluate historical documents quality. As we are eager to stick to it as closely as possible, the aim is to identify the criteria on which historians rely on to define a level of reliability of historical sources and data they contain.

We propose a new method in three steps (Fig. 10.4):

- Step 1: Historical critical analysis

Fig. 10.4 Evaluation of historical documents in three steps

A complete and precise critical analysis for each historical source studied has to be written by a historian. We propose an analysis based on 20 questions and three open comments organized in three sections (Document, Author, Event(s)). This critical analysis allows the introduction of a decision tree (see step 2) and the formulation of different answers supplied by this decision tree. The historical critical analysis is supplemented by a “system of filiation”, which allows to highlight the relationships that may exist between primary and secondary historical sources (copy, inspiration, etc.), as well as the identification of well-known sources used in literature [12, p. 593].

– Step 2: Rating of four criteria

Based on the critical analysis written by a historian (step 1), we developed a decision tree. It is based on four standardized criteria that can systematically be applied to any content and specificity of all primary or secondary historical sources. These criteria are: the type of the document, the author’s link to the testimony of an event, the cross-checking and the consistency of the source contents. Each criterion is a branch of this decision tree and consists of closed questions (yes/no) in order to ensure objectiveness. An example of one branch is given in Fig. 10.5. After following each branch, the user is left with four marks, one per criterion, which gives more than 1300 possible combinations. It is important to note that based on the critical analysis established in step 1, it is possible for everyone to give a score for each criterion in step 2.

– Step 3: Assigning a final score

A final score is assigned to the historical source and it is evaluated through an expert system. This innovative part of the method requires a combined mathematics

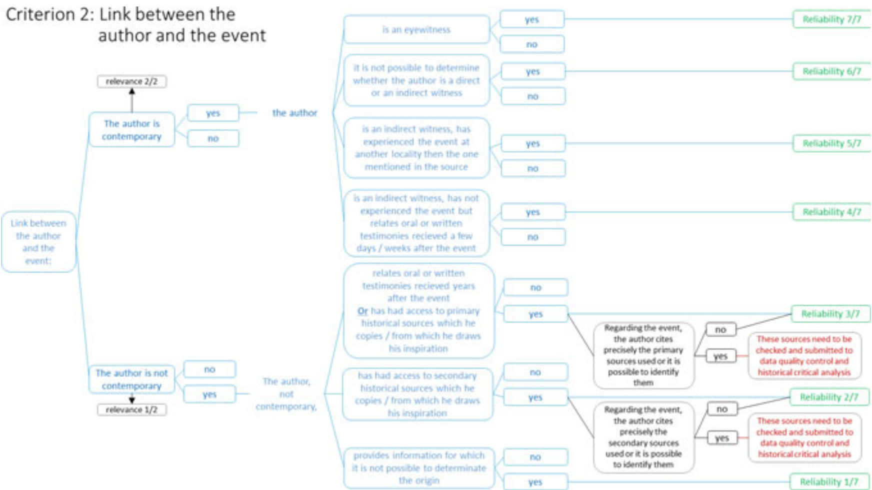


Fig. 10.5 Excerpt from the decision tree, branch 2: Criterion 2 - link to the testimony maintained by the author of the historical source evaluated

and history approach. Several hypothesis have been tested on 147 documents. The first expert system is a final consensual mark obtained by a rating done by historians. The second expert system is based on different weightings (light, medium, heavy) applied for each criterion and proposed by historians, which result in a simple linear function. The third expert system is based on algorithms to define the weightings of each criterion and thus set the final score. Finally, the last expert system is based on a neuroscience network. So far expert system 1, i.e. rating by historians, and expert system 2, i.e. linear function of crtiteria after weighting, have been compared, which gave a good correlation with a coefficient of determination $R^2 = 0.974$ (Fig. 10.6).

The application of this method in three steps gives a final score that represents the credit of the historical source and of the data it contains. This final score applies to primary or secondary historical source analyzed. The numerical value is expressed as a percentage of reliability. For this reason, a scale of value's range is proposed:

[0–20]%: not reliable at all;
[20–40]%: unreliable;
[40–60]%: moderately reliable;
[60–80]%: reliable;
[80–100]%: very reliable.

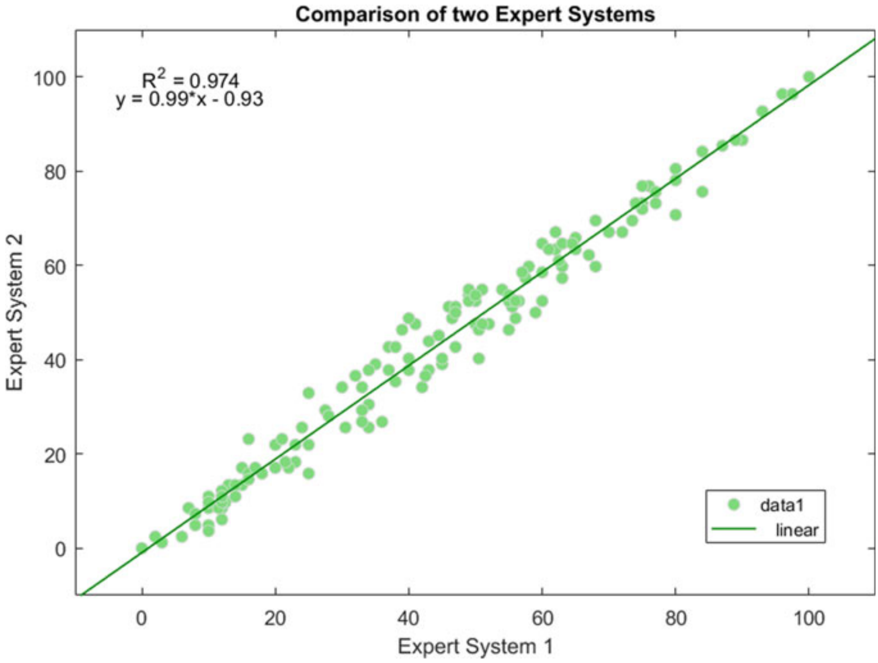


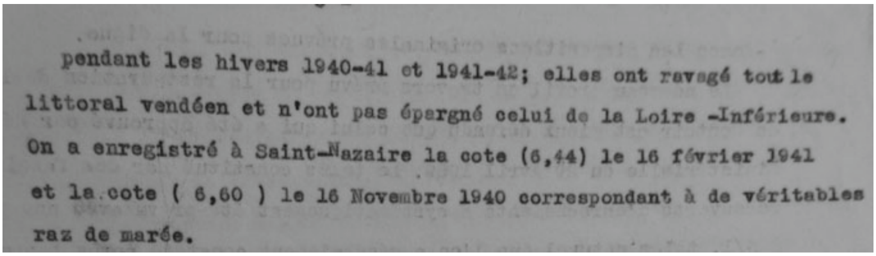
Fig. 10.6 Scores (in %) for 147 historical documents: comparison of expert system 1, i.e. a consual score given by historians, and expert system 2 based on different weightings (light, medium, heavy), i.e. a linear function, applied to each criterion. The correlation coefficient is very good, as $R^2 = 0.974$

The main advantage of this method is that it offers a rigorous and thorough approach to critical analysis that minimizes any subjectivity, as the historical critical analysis (step 1) is based on objective questions and comments and is done by historians who are experts of historical sources. The decision tree (step 2) is based on yes/no questions and the final mark is established using an expert system (step 3).

10.2.3 Case Studies: The Storms with Coastal Floodings of November 16, 1940 and February 15–16, 1941

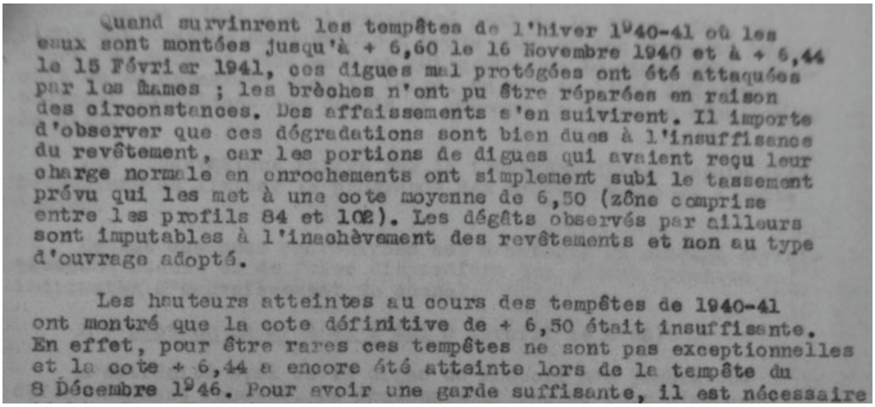
Two storms hit the French Atlantic coast on November 16, 1940 and February 15–16, 1941 causing big damages in the regions of Vendée and Loire-Inférieure. Many primary historical sources certify the occurrence of these coastal events. Furthermore, some traces of the 1940 storm were found in sedimentary records [41].

The two case studies presented in this work will focus on historical documents found in the French departmental archives of Loire-Atlantique (Departemental Archives of Loire-Atlantique, 365 W 124, Ponts-et-Chaussées engineer's report dated October 20, 1943 and Ponts-et-Chaussées engineer's report dated June 20, 1947 (Figs. 10.7 and 10.8)). After a precise historical critical analysis that can exclusively be performed by a historian (step 1 of the historical documents quality method presented above), they are evaluated with the decision tree (step 2) and a final score is set with an expert system (step 3). The results of step 2 and 3 for the documents are presented in Table 10.1. With a reliability of 98 or 96% and 84% depending on the expert system, the historical sources of Figs. 10.7 and 10.8 are considered as very reliable. The quantification of the historical skew surges for both storms in Saint-Nazaire can be carried out with good confidence.



pendant les hivers 1940-41 et 1941-42; elles ont ravagé tout le
littoral vendéen et n'ont pas épargné celui de la Loire -Inférieure.
On a enregistré à Saint-Nazaire la cote (6,44) le 16 février 1941
et la cote (6,60) le 16 Novembre 1940 correspondant à de véritables
raz de marée.

Fig. 10.7 Extract from a dike repair report, written by the Nantes Ponts et Chaussées engineer Mr Desbazeille and dated 10.20.1943. The water levels observed in Saint-Nazaire during the storms with seafloods of 10.16.1940 and 02.15–16.1941 are mentioned *Source* Departmental Archives of Loire-Atlantique, 365 W 124
Translation "[…] during the winter 1940–41 and 1941–42 ; they completely devasted the Vendée coast and did not spare the Loire-Atlantique coast. The sea levels rates (6.44) on February 16, 1941 and (6.60) on November 16, 1940 were recorded at Saint-Nazaire, corresponding to real tidal waves"



Quand survinrent les tempêtes de l'hiver 1940-41 où les eaux sont montées jusqu'à + 6,60 le 16 Novembre 1940 et à + 6,44 le 15 Février 1941, ces digues mal protégées ont été attaquées par les lames ; les brèches n'ont pu être réparées en raison des circonstances. Des affaissements s'en suivirent. Il importe d'observer que ces dégradations sont bien dues à l'insuffisance du revêtement, car les portions de digues qui avaient reçu leur charge normale en enrochements ont simplement subi le tassement prévu qui les met à une cote moyenne de 6,50 (zône comprise entre les profils 84 et 102). Les dégâts observés par ailleurs sont imputables à l'inachèvement des revêtements et non au type d'ouvrage adopté.

Les hauteurs atteintes au cours des tempêtes de 1940-41 ont montré que la cote définitive de + 6,50 était insuffisante. En effet, pour être rares ces tempêtes ne sont pas exceptionnelles et la cote + 6,44 a encore été atteinte lors de la tempête du 8 Décembre 1946. Pour avoir une garde suffisante, il est nécessaire

Fig. 10.8 Extract from a dike repair report, written by the Nantes Ponts et Chaussées engineer Mr Ballade and dated 06.20.1947. The water levels observed in Saint-Nazaire during the storms with seafloods of 10.16.1940 and 02.15–16.1941 are mentioned. *Source* Departmental Archives of Loire-Atlantique, 365 W 124. Translation: "When the winter storms of 1940–41 occurred, waters rose to + 6.60 on November 16, 1940 and to + 6.44 on February 15, 1941, these poorly protected dikes were attacked by waves; the breaches could not be repaired due to the circumstances (N.B: Second World War period) […]"

Table 10.1 Evaluation table of the two historical sources (application cases)

Historical primary source	Criterion 1: Type of the document	Criterion 2: Link between author and event	Criterion 3: Cross-checking	Criterion 4: Consistency	Final score in % (expert system 1)	Final score in % (expert system 2)
AD 44, 365 W 124, report of 10.20.1943	7/7	6/7	7/7	4/4	98	96
AD 44, 365 W 124, report of 06.20.1947	7/7	4/7	7/7	4/4	84	84

Moreover, the maximum water levels reached during these events are given in the source: 6.60 on 16th November 1940 and 6.44 during the night of 15th to 16th November (Fig. 10.7 and 10.8). No metric precision is given and no information on the location of the measurement is available. Still, the document is written by a engineer of the Ponts-et-Chaussées corps, owner of the tide gauge in the 1940s [11], so with good confidence the assumption can be made that the water levels in the reports are taken from tide gauge measurements, which were made in meters at that time [11]. So far, variable of uncertainties 8 and 9 have been handled, as the

Table 10.2 Water levels and surges for the storms of November 1940 and February 1941 in Saint-Nazaire in historical chart datum (calculated by Shom)

Date	OHD (m historic chart datum)	MLTGh (m historic chart datum)	MPh (m historic chart datum)	SS (m)
11.16.1940	6.60	6.61	5.19 (evening high tide)	1.41–1.42
02.16.1941	6.44	6.42	5.52 (morning high tide)	0.92–0.90

OHD: Observed sea level from historical documents (AD 44, 365 W 124)
MLTGh: Maximum sea level measured by the tide gauge not corrected to actual chart datum [11]
MPh: maximum predicted tide (harmonic analysis on contemporary tide gauge observations to estimate harmonic components)
SS: Resulting skew surge of OHD/MLTGh—MPh

data within the documents are consistent with the context and the reliability of the documents is very high. As both values are contemporary tide gauge data, variable 6, i.e. local hydrodynamic phenomena, can be excluded. Variable 7 doesn't need to be handled, as the documents are contemporary with both events, the engineer's reports have been published very few years after the occurrence of the storms.

The maximum water levels are still water levels, as they are assumed to be measured by a tide gauge. Thanks to the reconstruction of historical tide gauge data made by Yann Ferret, Shom [11], the water levels taken from the historical documents were compared to this tide gauge data. Table 10.2 shows that there are one or two centimeters of difference, and both data are in the same chart datum, i.e. chart datum in Saint-Nazaire has changed by 40 cm between 1938 to 1996 and 1996-present, so variable 4 is handled.

As mentioned before, there is a need for tidal prediction when reconstructing skew surges. For this case study we will estimate tidal predictions (variable 2) using two methods:

(a) Use of tide gauge data contemporary with the event and in contemporary chart datum.

This method is to be preferred, when enough contemporary tide gauge data is available. Here, a harmonic analysis is performed on two years of observations (1940–1941) to estimate tidal components and mean sea level. These are used to estimate tidal predictions (Table 10.2).

(b) Use of actual harmonic components.

When no contemporary tide gauge data is available, more recent tidal components are to be used, to estimate tidal predictions. In order to take into account changes in mean sea level, a correction has to be applied (variable 3). In this exemple we estimate a linear trend on annual mean sea levels (1,02 $mm.y^{-1}$). The mean sea level used to estimate tidal predictions is then corrected. The corrected result can not directly be compared to the water levels of the historical documents, as there has been a change in the vertical reference.

Therefore 40 cm have been added to the historical values, which correspond to the change in chart datum.

Tables 10.2 and 10.3 present the different skew surges (SS) estimated. To be consistent, the SS 1 shown in Table 10.3 should not be used as it does not include the mean sea level correction (variable 3). So the skew surge for November 16, 1940 (evening high tide) ranges from 1.33 to 1.42 m and from 0.89 to 0.92 m on February 16, 1941 (morning high tide), which is a very consistent result. It is important to highlight that the coastal flooding of February 1941 was mainly caused by dike breaches that were poorly repaired since the storm of November 1940. In fact, repairing the dikes in the context of the Second World War was no priority for the administration, politics and population (Fig. 10.8). As there is unfortunately no information on vertical land movements for the Saint-Nazaire area, variable 1 could not been handled. The differences of a few centimeters between the skew surges estimated using tide gauge data contemporary to the event, in ancient chart datum, and current tide gauge data (in current chart datum) can be explained by small variations in tidal components, resulting from sea level rise or changes in bathymetry (variable 5). Actual tidal components are estimated on recent tidal observations and reflect the current hydrodynamics, which may have been modified by artificialization of the harbor area, dredging of the channel or changes in mean sea level rise.

Finally, it should also be mentioned that not paying attention to the chart datum reference (i.e. −40 cm from 1938 to 1996 compared to 1996-present) can result in important errors. Indeed, using the observed sea level from historical documents (AD 44, 365 W 124) not corrected to actual chart datum and the maximum predicted tide with correction of mean sea level in actual chart datum can lead to underestimate the historical skew surges: their quantification being respectively of 0.93 m and 0.51 m.

Table 10.3 Water levels and surges for the storms of November 1940 and February 1941 in Saint-Nazaire in actual chart datum (calculated by Shom)

Date	OHD40 (m actual chart datum)	MLTG (m actual chart datum)	MP (m actual chart datum)	MPmsl (m actual chart datum)	SS 1 (m)	SS 2 (m)
11.16.1940	7.00	7.01	5.75	5.67	1.25–1.26	1.33–1.34
02.16.1941	6.84	6.82	6.01	5.93	0.83–0.81	0.91–0.89

OHD40: Observed sea level from historical documents (AD 44, 365 W 124) + 40 cm to correct change in chart datum [11]
MLTG: Maximum sea level measured by the tide gauge corrected to actual chart datum [11]
MP: Maximum predicted tide without correction of mean sea level (use of actual tidal components and actual mean sea level)
MPmsl: Maximum predicted tide with correction of mean sea level (use of actual tidal components, correction of mean sea level applying a linear trend of 1.02 $mm.y^{-1}$)
SS1: Resulting skew surge of OHD40/MLTG—MP
SS2: Resulting skew surge of OHD40/MLTG—MPmsl

10.3 Conclusions

In conclusion, this interdisciplinary study provides interesting results and it shows that:

- by paying attention to some potential causes of uncertainties (changes in sea level, criticism and evaluation of historical documents quality, operative chart datum reference, etc.),
- by ensuring the reliability of historical sources and data through the use of the historical documents quality method,
- by deepening historical researches in archives and
- by a mix of different scientific fields and methods

it is possible to reduce uncertainties and errors in the quantification of historical skew surges.

This collaboration between history, geography, geology, engineering and mathematics provides important and relevant historical data for the statistics of extremes. More reliable, precise and robust quantification of historical skew surges is possible, thanks to (a) the quality of the documentation used, (b) huge variety of historical sources and datasets used, and (c) the integration of the majority of the uncertainties. Moreover, even if some of these uncertainties were not able to be quantified and taken into account on the computation of historical skew surges, these uncertainties will be considered in the statistics of the extremes. In that case, an idea of the possible accuracy made in the computation of historical skew surges must be known.

To conclude, a challenging perspective could be the modeling or the numerical simulation of past storms [30]. Numerical simulation and modeling can help to quantify some further uncertainties as the effect of the changes in bathymetry over the time or the risk of "corridor/funnel" phenomenon (local hydrodynamic phenomena) and to increase the accuracy of the computed historical skew surges.

Acknowledgements Authors wish to acknowledge the other members of the Working Group "Historical Storms and Floodings", especially Yann Ferret and Gaël André (SHOM).

Part of these researches have been funded through EDF R&D research project MOISE.

References

1. Albini P, Musson R, Gomez Capera A, Locati M, Rovida A, Stucchi M, Vigano D (2013) Global historical earthquake archive and catalogue (1000–1903), GEM Technical Report, [online]
2. Andreevsky M, Kergadallan X, Bernardara P, Benoît M, Gaufrès P, Trmal C (2012) Comparaison de différentes méthodes d'estimation des niveaux marins extrêmes en site à fort et à faible marnage. In : Evénements extrêmes fluviaux et maritimes. Leurs variabilités spatiales et chronologiques dans l'ouest de l'Europe. 34e Journées de l'hydraulique, pp 1–12
3. Athimon E (2021) Tempêtes et submersions marines sur les territoires de la côte atlantique (XIVe-XVIIIe siècle), Saintes. Les Indes Savantes

4. Van Bavel B, Curtis D, Hannaford M, Moatsos M, Roosen J, Soens T (2019) Climate and society in long-term perspective: opportunities and pitfalls in the use of historical datasets. Wires CC 10–6:e611
5. Benito G, Lang M, Barriendos M, Llasat C, Francès F, Ouarda R, Thorndycraft V, Enzel Y, Bardossy A, Coeur D, Bobée B (2004) Use of systematic, palaeoflood and historical data for the improvement of flood risk estimation. Rev Sci Methods. Natl Hazards 31:623–643
6. Breilh J-F, Bertin X, Chaumillon E, Giloy N, Sauzeau T (2014) How frequent is storm-induced flooding in the central part of the Bay of Biscay ? Global Planet Change 122:161–175
7. Bulteau T, Idier D, Lambert J, Garcin M (2015) How historical information can improve estimation and prediction of extreme coastal water levels: application to the Xynthia event at La Rochelle (France). Nat Hazard 15–6:1135–1147
8. Chaumillon E, Bertin X, Fortunato AB, Bajo M, Schneider JL, Dezileau L, Walsh JP, Michelot A, Chauveau E, Créach A, Hénaff A, Sauzeau T, Waeles B, Gervais B, Jan G, Baumann J, Breilh JF, Pedreros R (2017) Storm-induced marine flooding: lessons from a multidisciplinary approach. Earth-Sci Rev 165:151–184
9. Corvol A (dir.) (2005) Tempêtes sur la forêt française, XVI^{e}-XX^{e} siècle. Paris. L'Harmattan
10. Daubord, C., André, G., Goirand, V., Kerneis, M. (2014). *Rapport technique final du projet Nivext*. SHOM.
11. Ferret, Y. (2016). *Reconstruction de la série marégraphique de Saint-Nazaire*. Rapport technique. SHOM.
12. Fradet T (2016) Vulnérabilité et perception face aux tremblements de terre en France, 1650–1850. PhD. Saint-Quentin University, Saint-Quentin
13. Frau R (2018) Utilisation des données historiques dans l'analyse régionale des aléas marins extrêmes : la méthode FAB. PhD. Paris-Est University, Paris
14. Frau R, Andreevsky M, Bernardara P (2018) The use of historical information for regional frequency analysis of extreme skew surge. Natl Hazards Earth Syst Sci 18:949–962
15. Garnier E, Surville F (dir.) (2010) La Tempête Xynthia face à l'histoire. Submersions et tsunamis sur les littoraux français du Moyen Âge à nos jours, Saintes, Le Croît Vif
16. Gattacceca J (2009) Etude de l'estuaire souterrain dans la lagune de Venise à l'aide des isotopes duradium et du radon. PhD. Paul Cézanne University, Aix-Marseille
17. Giacona F, Eckert N, Martin B (2017) A 240-year history of avalanche risk in the Vosges Mountains basedon non-conventional (re)sources. Natl Hazards Earth Syst Sci 17:887–904
18. Giloy N, Hamdi Y, Bardet L, Garnier E, Duluc CM (2018) Quantifying historic skew surges: an example for the Dunkirk Area, France. Natl Hazards, pp 1–25
19. Giloy N, Latapy A, André G, Pouvreau N, Bardet L, Migaud A (2022) The impact of tidal predictions on historical extreme skew surges, poster, 5th EVAN Conference, Orlando
20. Glaser R (1996) Data and methods of climatological evaluation in historical climatology. Hist Soc Res 21:56–88
21. Gottschalk E (1971–1977) Stormvloeden en rivieroverstromingen in Nederland, vol 3. Assen. Van Gorcum
22. Gouriou T (2012) Evolution des composantes du niveau marin à partir d'observations de marégraphie effectuées depuis la fin du 18^{e} siècle en Charente-Maritime. PhD. University of La Rochelle, La Rochelle
23. Gram-Jensen IB (1985) Sea floods. Contributions to the climatic history of Denmark. Danish Meteorological Institute. Copenhague
24. Haigh I, Wadey M, Gallop S, Loehr H, Nicholls RJ, Horsburgh K, Brown J, Bradshaw E (2015) A user-friendly database of coastal flooding in the United Kingdom from 1915–2014. Sci Data 2–1:1–13
25. Haigh I, Wadey M, Wahl T, Ozsoy O, Nicholls R, Brown J, Gouldby B (2016) Spatial and temporal analysis of extreme sea level and storm surge events around the coastline of the UK. Sci Data 3:160107
26. Halkin L (1951) Initiation à la critique historique. Armand Colin, Paris
27. Hamdi Y, Bardet L, Duluc C-M, Rebour V (2015) Use of historical information in extreme-surge frequency estimation the case of marine flooding on the La Rochelle site in France. Nat Hazard 15–7:1515–1531

28. Hamdi Y, Garnier E, Giloy N, Duluc CM, Rebour V (2018) Analysis of the risk associated to coastal flooding hazards: a new historical extreme storm surges dataset for Dunkirk, France. Natl Hazards Earth Syst Sci 417, [Online]
29. Hickey K (1997) Documentary records of coastal storms in Scotland, 1500–1991 A.D. vol 2. Ph.D. Coventry University. Coventry
30. Idier D, Rohmer J, Pedreros R, Le Roy S, Lambert J, Louisor J, Le Cozannet G, Le Cornec E (2020) Coastal flood: a composite method for past events characterisation providing insights in past, present and future hazards joining historical, statistical and modelling approaches. Nat Hazards 101:465–501
31. De Kraker A (2006) Flood events in the southwestern Netherlands and coastal Belgium, 1400–1953. Hydrological Sciences, Special Issue : Historical Hydrology 51–5:913–929
32. Lamb H, Frydendahl K (1991) Historic storms of the North sea. Cambridge University Press, British Isles and Northwestern Europe. Cambridge
33. Lambert J (1986) Actualisation et interprétation des données de sismicité historique relatives au Bassin Aquitain et au Quercy. Rapport technique. BRGM
34. Lang M, Cœur D, Audouard A, Villanova Oliver M, Pene JP (2017) BDHI: a french national database on historical floods. FLOODrisk 2016. Lyon
35. Langlois CV, Seignobos C (1898) Introduction aux études historiques. Hachette, Paris
36. Le Goff J, Nora P (dir) (1974) Faire de l'histoire, I. Nouveaux problèmes, II. Nouvelles approches, III. Nouveaux objets. Paris, Gallimard
37. Lemercier C, Zalc C (2008) Méthodes quantitatives pour l'historien. La Découverte, Paris
38. Porfido S, Esposito E, Alaia F, Molisso F, Sacchi M (2009) The use of documentary sources for reconstructing flood chronologies on the Amalfi rocky coast (southern Italy. In: Violante C (ed) Geohazard in Rocky coastal areas. London. The Geological Society
39. Pouzet P, Maanan M (2020) Climatological influences on major storm events during the last millennium along the Atlantic coast of France. Sci Rep 10:12059
40. Pouzet P, Maanan M, Schmidt S, Athimon E, Robin M (2019) Correlating three centuries of historical and geological data for the marine deposit reconstruction of two depositional environments of the French Atlantic coast. Mar Geol 407:181–191
41. Pouzet P, Maanan M, Robin M (2019a) La tempête de 1940 détectée dans les sédiments des Traicts du Croisic. Les Cahiers Nantais, IGARUN, pp 3–14
42. Péret J, Sauzeau T (2014) Xynthia ou la mémoire réveillée. Gestes, Paris
43. Santamaría-Gómez A, Gravelle M, Dangendorf S, Marcos M, Spada G, Wöppelmann G (2017) Uncertainty of the 20th century sea-level rise due to vertical land motion errors. Earth Planet Sci Lett 473:24–32
44. Scotti O, Baumont D, Quenet G, Levret A (2004) The France macroseismic database SISFRANCE: objectives, results and perspectives. Ann Geophys 47:571–581
45. Tabeaud M, Lysaniuk B, Schoenenwald N, Buridant J (2009) Le risque « coup de vent » en France depuis le XVIe siècle. Annales de géographie 667:318–331
46. Torres-Vera MA (2010) Historical seismicity in Mexico during 1568–1837: intensity evaluation and data reliability. Nat Hazards 54:863–878
47. Veale L, Endfield G, Davies S, Macdonald N, Naylor S, Royer MJ, Bowen J, Tyler-Jones R, Jones C (2017) Dealing with the deluge of historical weather data: the example of the TEMPEST database. Geo: Geogr Environ 4–2:e00039
48. Weiss J (2014) Analyse régionale des aléas maritimes extrêmes. PhD. Paris-Est University, Paris
49. Wöppelmann G, Marcos M (2016) Vertical land motion as a key to understanding sea level change and variability. Rev Geophys 54–1:64–92
50. https://www.sonel.org
51. https://www.sonel.org/-Vertical-land-movement-estimate-.html?lang=en