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Quantifying historic skew surges: an example for the Dunkirk Area, France

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ABSTRACT

As instrumental records often cover only short time periods, historical information is the main source of data in order to extend natural disaster catalogues. This study aims to show the feasibility of quantifying extreme sea levels and skew surges during storm events by using historic documentary data. The documentary data related to the extreme events is often not freestanding enough to directly extract water levels and subsequently skew surge levels, hence auxiliary information such as dike sketches was used to interpret the collected data. First a strategy for the reconstruction of historic levels is presented which implies an analysis on three different scales: (i) the data scale, (ii) the quantification scale and (iii) the event scale. Strong hypotheses were made during the quantification processes of the seven historic skew surges. Therefore the methodology also aims to trace the hypotheses taken for the surges reconstruction, to inform potential users about the different degrees of reliability of estimated values. Secondly this strategy is applied on an existing database of storms and storm surges that occurred in Dunkirk in the north of France, which contains 75 events. Within this database the focus was set on seven surge events that hit Dunkirk between 1778 and 1846 and seven new skew surges were estimated for that period.

Key words: storm surges, historical archives, coastal flooding

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1 INTRODUCTION

Storms and their associated storm surges are known to be extreme events impacting in particular low-lying coastal areas. In Europe such areas can be found in the northwestern part of the continent and have been the subject of multiple flooding during the past. During the first years of the 21st century, major surge events already occurred on the western European coastline such as the storm Xaver and its associated surges that severely hit North-Western Europe in the beginning of December 2013 or storm Xynthia that severely hit the central French Atlantic Coast in February 2010 causing the death of more than 47 people and over 1.5 billion euros of damage (Bertin et al. 2012; Breilh et al. 2013; Spencer et al. 2015).

In both cases, these extreme water levels are a result of the coincidence of the high tide and the surge that accompanied the storms. Skew surges, defined as the difference between the highest observed water level which is measured by a tide gauge for example and the closest astronomical high tide which can be predicted (Haigh et al. 2015; Pugh and Woodworth 2014), are of huge interest for coastal protections. For instance, the French regulation for nuclear safety (ASN) requires the coastal facilities to be protected against the reference level which consists of the sum of:

- the highest astronomical tide (HAT),
- the upper bound confidence interval 70% of the 1/1000 skew surge,
- and the extrapolation of the sea level rise (ASN 2013).

In France on the Atlantic and Channel Coast, although there were two long tide gauge series starting before the 1850s, the mean length of the tide gauge series is shorter than 40 years (Ferret 2016; SHOM 2017a). Therefore, using these short tide gauge series for estimating extreme events like the 1000-year return level of skew surges appears challenging. Performing a frequency analysis using short tide gauge records leads to poor fitting and large confidence intervals at the tail of the distribution, in particular when these records contain an outlier. The value of using other sources of data as historical information in the frequency estimation of extremes has been recognized by several authors (e.g. (Gaál et al. 2010; Hamdi 2011; Payrastra et al. 2011), or (Bulteau et al. 2015; Hamdi et al. 2015) for coastal flooding hazard.

Data rescue to reconstruct long tide gauge series is undergoing all over the world, as these measurements enable a better estimation of the evolution of the long-term local and global sea level rise and as they highlight extreme events (Dangendorf et al. 2014; Ferret 2016; Gouriou 2012; Pouvreau 2008; Talke and Jay 2017). In the absence of instrumental data, it is possible to reconstruct climate and hydrometeorological extremes on the basis of man-made data (Brázdil 2000). (Pfister et al. 2010) used chronicles, poems, or historic institutional data from across western European countries to reconstruct winter storms and the associated storm tracks in this area. (De Kraker 1999) reconstructed the storm variability in the Netherlands during the Middle Age by using the reports of dike accounts in which damages following storms and gales were reported. More recently (Garnier et al. 2017) provided an analysis of historic storms through five case studies in Europe. But not only storm tracks or frequencies were derived from historic data, it is also possible to quantify extreme water levels and subsequently the surges. (Baart et al. 2011) used historic paintings in order to reconstruct historic beach profiles. These profiles were then integrated into a numerical model to estimate the surge of a storm in the 18th century that affected the Netherlands. (Breilh et al. 2014) combine information from archives and modeling to analyze coastal floods of the 20th century for La Rochelle, France.

Dunkirk has been selected as a study site as (i) it has the highest known skew surge in France: for the disastrous storm of 31st January – 1st February 1953, values higher than 2.10 m were reconstructed, as the tide gauge was not yet operational (Bardet et al. 2011; Le Gorgeu and Guitonneau 1954; Weiss 2014) and (ii) as it is used as the reference station for the Gravelines Nuclear Power Plant, located 20 km west of Dunkirk. The current Dunkirk tide gauge has been operational since 1956 and (Latapy et al. 2017) showed that historic sea level observations exist. Still, these observations were made during short periods and the data is still being analyzed by these authors.

This study is the continuation of works started by (Hamdi et al., 2017 *in review*) who created a new database of storm and flooding events which hit the Dunkirk area for the period of 1500 to 2000. Further, the authors used quantitative historic information specifying the water levels reached during three events from 1720-1767 and estimated the associated skew surges. A second main objective of their work was to perform a local frequency analysis using historical information.

As unfortunately no more quantitative sources were found for the more recent period this study proposes a methodology for the reconstruction of historic water levels and associated skew surges for the late 18th and 19th centuries using qualitative sources and combining these with historic maps and sketches of dikes.

The paper is structured as follows: In section 2 a brief overview of the study area and the database used is given. The methodology used to reconstruct total water levels and skew surges using historic data is presented and

applied to the study case Dunkirk in section 3. A much more detailed chronicle of the Dunkirk harbor as well as the detailed reconstruction of the events can be found in the appendix. Section 4 discusses the methodology and the results obtained. Finally, the main results are summarized, and some perspectives are presented.

2 STUDY SITE

2.1 GEOGRAPHIC AND MORPHODYNAMIC SETTING

Located close to the Belgium border, Dunkirk is the first major city on the southern coastline of the North Sea (Figure 1). The coastline is essentially formed by coastal dunes on wide dissipative macrotidal beaches, where important erosion has been observed since at least the middle of the 19th century. The semidiurnal tides have a mean tidal range during mean spring tides of 5.6 m and of 3.5 m at mean neap tides in Dunkirk. Winds parallel to the shore from a south to southwest direction are dominant. During the winter months northerly onshore winds occur that can cause storm surges when combined with low atmospheric pressure (Maspataud et al. 2013; Schmitt et al. 2017; Vasseur and Hequette 2000).

Since the 20th century the coastal dunes have given way to massive urbanization and industrialization of the shoreline especially in the area between Dunkirk and Gravelines. In fact, the massive extension of the Dunkirk harbor area and the implantation of the nuclear power plant of Gravelines in the 1970s have completely artificialized the coastline (EDF 2017; Maspataud et al. 2013). Today the area of Dunkirk is densely populated with more than 2000 inhabitants per square kilometer (INSEE 2017).

2.2 HISTORY OF DUNKIRK

Dunkirk was first mentioned in 646 when Saint Eloi had built a church in the dunes, which he called “*Dune Kercke*” meaning “the church in the dunes”. The location of the city of Dunkirk and its prospering trade made the city a strategic point on the Flemish coast. The brief historic aspects presented below mainly cover the evolution of the harbor and the port infrastructure, which has been significantly modified throughout history. A more complete evolution of the city can be found in Appendix 1.

Due to its strategic location, Dunkirk was the subject of three peace-treaties (Treaty of Utrecht 1713, Treaty of Aix-la-Chapelle 1748, Treaty of Versailles 1783) during the 18th century, which each stipulated the entire or partial destruction of the harbor infrastructure of Dunkirk. From the late 18th century up to the Second World War, the infrastructures were rebuilt on the remaining remnants. With the arrival of the railway in the 19th century the industrial and harbor zone expanded towards the shoreline. At the end of the Second World War and the German occupation, the city of Dunkirk was 90% destroyed and the harbor almost annihilated. The reconstruction as well as a massive process of extension of the harbor area began and today the port is capable of accommodating all types of goods and the largest vessels (22m draft). It has two maritime entrances and extends for 17 km along the coast between Dunkirk and Gravelines and occupies an area of about 7000 hectares (Port Autonome de Dunkerque 2017a; Port Autonome de Dunkerque 2017b).

2.3 EXISTING DATABASE

The database of storms and storm surges created by (Hamdi et al., 2017 *in review*) for Dunkirk was used for this study. It contains a total of 73 historic events for the period from 1507 to 2000, divided in 40 events with which marine flooding can be associated and 33 other storms without flooding evidence. Figure 2 shows the temporal distribution of these events.

Each single source was submitted to data quality control, using the degree of reliability scale proposed by (Hamdi et al., 2017 *in review*). This scale classifies the type of source, whether it is a primary source or a secondary source with different levels of information. It does not qualify the content of the source. The event description can then be ordered in two groups: sources with quantitative or qualitative information. Sources containing numerical information about water levels are considered to be quantitative information. Qualitative sources describe the event without any quantifiable information.

(Hamdi et al., 2017 *in review*) already identified three major surge events for the period from 1720 – 1767. As total water levels are given by one source, a first attempt at skew surge quantification was made. For the period of 1770 – 1900 six other major flooding events were identified, but only qualitative data describes these events.

3 METHODOLOGY AND RESULTS

3.1 GENERAL APPROACH

The strategy used to quantify historic levels and estimate skew surge levels was to rely on the descriptive data available and put it into historical and geographical context using auxiliary sources such as historic maps, engineer's reports, sketches of quays or dikes. Figure 3 represents the outline of the entire methodology which will be described below.

On a data level, each source was submitted to data quality control. Sources were qualified in terms of their type, whether they are an original document or secondary source. This work has already been done by (Hamdi et al., 2017 *in review*) and we refer to this paper for more details.

In order to estimate accurate historic levels, hypotheses were made, which are detailed below.

The first assumptions appear when quantifying the height of quays or infrastructures using historic sketches. Sketches providing no scale bar or height indication unfortunately could not be used. In the cases where measurement units or scale bars are given, it cannot always be said with certainty (i) which exact measurement unit is given and (ii) that the sketches have been drawn in the right proportions. Assumptions may also be made when interpreting sketches or plans, for example interpreting a blue line as a mean water level. These kinds of hypotheses were traced by a *A-Flag* which was added as a warning to the quantified historic level. Another important topic during the quantification is the spatial and temporal consistency of the data used to reconstruct water levels. For example, when data sources only mentioned "*flooded quays*" without specifically mentioning which quay is meant, attempts can be made to estimate a water level for locations where auxiliary data is available. This reconstructed value is then tagged with an *S-Flag*, highlighting that a spatial hypothesis was taken. Reconstructed values are tagged with a *T-flag*, when hypotheses were taken on the temporal consistency of the data used for reconstruction: If no auxiliary information for exactly the same time frame as one event is available, sketches from earlier or later periods can be helpful for the reconstruction of historic levels.

Once historic water levels are estimated, predicted water levels are used to estimate historic skew surges. The predicted high tide level for an historic event can be estimated using recent tide records and applying a mean sea level trend. In this study, tide gauge data are obtained from the data portal of SHOM (National hydrographic and oceanographic service) in France (SHOM 2017a). Harmonic analysis is performed on this tide data using the R package *TideHarmonics* developed by (Stephenson 2015). A correction of sea level rise is then applied. Hourly predictions for the time of the storm events were made and the interpolation of these data allowed the extraction of the highest predicted water levels, which, subtracted from the reconstructed flooding levels, give skew surge levels.

The last step of the methodology is to put the event and the quantified levels in a more general scale than the reconstructed value itself and comments can be added if necessary, to notify potential users about a specific point of reconstruction. The more sources and high quality sources there are, the better the event may be described. The more hypotheses are made during the quantification step, the less the reconstructed surge is freestanding and bound to these hypotheses. Finally, a comment addressed to the users may influence a values' robustness.

3.2 APPLICATION TO THE STUDY SITE

The aforementioned approach was applied to the reconstruction of water levels of the six flooding events that were identified by (Hamdi et al., 2017 *in review*); a seventh event was detected and added to the database within this study.

For the estimation of tidal prediction, the following corrections of sea level rise were undertaken: (Wahl et al. 2013). found that the North Sea sea level was relatively stable till the end of the 19th century. For the period of 1900-2011 a linear absolute sea level trend for the North Sea region of 1.53 mm.year⁻¹ was determined by (Wahl et al. 2013), which is consistent with the linear trend obtained by annual means of the Dunkirk tide gauge series (1.44 +/- 0.20 mm.year⁻¹ for the period of 1956-2016, and -0.11 mm.year⁻¹ of GIA adjustment according to Peltier's ICE5GV1.3(VM2) models output obtained on the PSMSL website (Peltier 2004)). Using this trend, the mean sea level of 1890 was estimated for Dunkirk and was then considered to be the same for the seven events analyzed in this study.

Table 1 shows the data quality of the available sources that describe an event, the reconstructed total water levels (TWL), the flags associated to the reconstruction using the above-given methodology, the estimated skew surge and the location where the water levels were reconstructed for the major events that hit Dunkirk between 1770 and 1900. The details on the reconstruction of the TWL and the associated skew surges for the seven events can

be found in Appendix 2. Though the reconstruction in the appendix presents heights with two decimals i.e. a centimetric accuracy, the authors decided to present rounded values in the current paper.

For the events selected, the quality of the sources are good, as they have been categorized as type 3 (i.e. a secondary source clearly specifying its archival sources) or 4 (i.e. a primary source).

Total water levels are reconstructed at different points of interest in the harbor area (at its entrance or further in the center of the harbor) and vary from 7.0 m to 8.2 m chart datum. Figure 4 shows the location of the reconstructed water levels. The water levels are considered to be minimum water levels when sources only mention that “*quays have been flooded*” (Bossaut 1898; Bottin 1811; Derode 1852; Lemaire 1857) as the reconstructed water level then corresponds to the height of the quay. For the events of 1807 and 1808, the sources relate a “*15 inches*” and a “*34 inches*” flooding, respectively “*above the top of the woodwork quay on the side of the city center*” (Bottin 1811), the water levels in meters are then considered to be approximate values. Due to the lack of precision of the flooded quays, multiple locations were used to reconstruct water levels if possible, resulting in multiple water and surge levels for all events.

The events from 1846 have two skew surges for the same location. The data available did not specify the time at which the two floods occurred, so both high tides of each day were used to estimate the skew surge. The water reconstructed water levels reach the water levels of the 1953 storm (Le Gorgeu and Guitonneau 1954). Still, while the quality of the one source is good, it was not possible to crosscheck these two events in national or international databases, which is why a comment is addressed to the potential users of these two values.

The associated estimated skew surges vary from 1.1 m up to 2.6 m, or up to 2.2 m without considering the 1846 events. As indicated for the total water levels, the skew surges correspond either to minimum values or to approximate values. Still for further works these values have to be used with caution as the flags added to the reconstructed values highlight: Unfortunately all values are bound to hypothesis and so far no water and skew surge level could be estimated without making assumptions.

4 DISCUSSION

In order to estimate extreme historic water levels and in absence of historic instrumental or tide gauge data, the use of descriptive sources is suggested. A methodology is proposed to reconstruct total water levels and subsequently skew surges using information gathered in archives and historic documents. This methodology consists of three steps of analysis from a micro to a macro scale, which was then applied to the study site.

4.1 GENERAL METHOD

The first scale, data scale, consists of analyzing the documentary data. It is important to notice how information from a data source can be crosschecked and the event description can be compared. The more this information converges, the better the course of this event can be traced. Sources were also categorized by their type, whether it is a primary source, i.e. category 4 and highest quality, or a secondary source giving good, poor or no information about the primary source, categories 3, 2 and 1 respectively. There is still a limitation regarding the content of the source. So far, all information was taken as written without any interpretation. But how can the content be judged, when no crosschecking with other sources is possible?

When combining the data from the database with the auxiliary data for the estimation of water levels, spatial and / or temporal hypotheses were made. These hypotheses must be traceable until the end of the analysis process to give or take away a values’ robustness. The hypotheses are built on the quantity and quality of the documentary and auxiliary sources available. If, during further research, new documentary sources or sketches are to be found, these hypotheses may be modified or excluded. Three different flags were displayed to identify the hypotheses made during the reconstruction and used throughout the study, but is possible to add other flags for other studies of this kind, such as the influence of river discharge or wave influence, depending on the context given.

4.2 DUNKIRK STUDY SITE

Applying the methodology to the study site using the (Hamdi et al., 2017 *in review*) database, resulted in water and skew surge levels for seven events from 1778 to 1846 for the city of Dunkirk. The reconstructed water levels are considered to be total water levels; the influence of waves is neglected in this study as unfortunately no details about waves are given in the event description. Therefore, when the sources mentioned a flooded quay, the assumption was made that the total water level reached at minimum the height of the quay. Throughout history channels were built in the city to drain the marshes and to allow navigation between coastal and hinterland cities. The discharge of the sluices was also used to increase the dredging of the main channel that leads to the open seas and therefore the influence of rivers was neglected within this study.

Comparing the estimated reconstructed skew surges to the systematic surges, i.e. surges from the tide gauge period, all historic surges appear to be almost at least as high as the highest systematic surge, which is estimated at 1.30 m. As shown in table 1 the numeric values of the skew surges vary from 1.1 m up to 2.6 m, though not one has been built without a hypothesis. Figure 5 shows the reconstructed skew surge heights obtained from (i) the tide gauge data, (ii) quantified surges from the literature and (iii) the reconstructed values from this study. Skew surges were plotted on the same graphic, as here the hypothesis is made that water levels measured at the tide gauge and the different locations of Dunkirk harbor are comparable.

High-frequency tide gauge data has only been available since 1956 for Dunkirk, so unfortunately no conclusions on the modification of harmonic constituents can be drawn for the 19th century or the early 20th century. It is not clear how the repeated digging and dredging of the channel and its constant modification and artificialization may have influenced the local hydrodynamics throughout time as major modifications were made at the end of the 19th century when the new docks were dug on land gained from the seas. Still, historic tide gauge data from Dunkirk is currently being digitized and reconstructed at SHOM and the University of Cote d'Opale: (Latapy et al., 2017) found approximately 10 years of high frequency data between 1865 and 1875. Once this data has been reconstructed, a detailed analysis of harmonic constituents may be done, if the data quality is good. Further, it has to be noted that the current tide gauge is situated in the entrance of the harbor, which implies that the predicted water levels may differ within the inner harbor area, where the reconstructed surges were estimated. As it was already pointed out by (Bulteau et al. 2015) hydrodynamic modeling could help estimate the difference between water levels at the entrance of the harbor area, i.e. at the tide gauge location, and the locations in the inner part of the harbor.

Not in terms of accuracy but in terms of exhaustiveness, the authors are quite confident that, relying on the documents available in the updated database (Hamdi et al., 2017 *in review*); for the period between 1720 and 1825 the highest water levels were identified. For the period 1720-1767 the highest water level was in 1767 according to de Fourcroy de Ramecourt (De Fourcroy de Ramecourt 1780; De Lalande 1781). For the period 1791 – 1808, there is good evidence to believe that no higher water level occurred during that period, as the event of 1808 was said to be higher than 1807 (Bottin 1811) and higher than 1791 (Journal Politique de Mannheim 1808b). The high water of 1778 occurs in between these two bounds, and according to the documents available so far there is good evidence to believe that no other extreme water level occurred between 1767 and 1791. Except for the storm of February 1825, no information on any flooding is available for the period of 1808-1825. For the period 1825-1897 it is more difficult to be exhaustive. The only two events quantifiable were those that happened in 1846, but only one source relates these events. There are storm events for the period, but almost no mentions of flooding of the urban territory of Dunkirk. A potential explanation for this might be that during the 19th century the docks, dikes and quays were reconstructed and the infrastructures were heightened.

The database and the reconstructed values may be used for further work by public policies for urban and coastal planning / management in the Dunkirk area. Knowing that high water levels and flooding comparable to or higher than contemporary events occurred in the past may reactivate a risk culture that can be used to sensitize populations.

Although the historical information often lacks precision, it has been shown that it improves the frequency estimation of extreme events in frequency analysis. A review of the literature on historical information and the role it can play in a frequency analysis has been made by several authors (e.g., Stedinger and Baker, 1987; Salas et al., 1994; Ouarda et al., 1998). Still, since the water level reconstructions at different locations have been done using strong assumptions, which are shown by the flags associated to values, the heights remain either estimation or lower bounds, as reconstructed water levels are in most cases the height of quays which they overtopped. Due to their historic character they should be integrated carefully and differently into a frequency analysis.

5 CONCLUSION

There is a need for historic information, when estimating high return periods. So far, the estimation of the 1/1000 skew surge is done by using the systematic surges obtained by the tide gauge data. When no or poor historic tide gauge or instrumental data is available, the authors suggest using historical documents available in archives to estimate historic water levels.

The proposed methodology is an analysis from a micro scale, i.e. the analysis of the historic data for each specific source and the associated quantification; to a macro scale, i.e. the consideration of the complete information for the event. Complementary data, called auxiliary data were used to put the information from each

source in their geo-historical context. For the reconstruction various kinds of levels of uncertainties are traced with flags in the database: the quality of each documentary source mentioning a storm or a surge; and the reliability of the water or surge level, which involves several hypotheses.

This methodology was applied to the city of Dunkirk, which has, so far, the highest known skew surge in France. The (Hamdi et al., 2017 *in review*) storm and surge database was used and complemented. The search for information did not only focus on storm or marine flooding events but was extended also to background information of the city and the considered study region, to set the geo-historical background of the study. The auxiliary data set contains mainly historic maps of Dunkirk and sketches and profiles of quays in the city for different time periods, but also chronicles of the historic evolution of the city.

Within the database seven events that occurred between 1778 and 1846 were analyzed more closely and put into the geo-historical context with the aim of estimating skew surge values. These selected events are described by qualitative data, poor or no quantified data is available. Nevertheless, applying strong hypotheses helped estimate water levels and skew surge heights for seven of these events, the skew surge heights range from 1.1 m to 2.6 m and are as high as the highest systematic skew surges. So far the two events from 1846 having the highest surges couldn't be crosschecked. All skew surge values are in the range of the highest systematic skew surges and the highest observed surge in 1953. Still, these water levels depend on the documents available and on the hypothesis made during the quantification process. New evidence and another description of the storm and the flooding event may either reinforce or question the reconstructed water levels.

Further research could help to thoroughly analyze how the additional data could improve the characterization of coastal hazards and what the impact will be of the gathered historical information on the frequency estimation of extreme storm surges and sea levels.

APPENDIX 1: HISTORY OF DUNKIRK

The location of the city of Dunkirk and its prospering trade had made the city a strategic point on the Flemish coast. The historic aspect presented afterwards will mainly cover the evolution of the harbor and the port infrastructure. For the reconstruction following works were used (Chambre de Commerce de Dunkerque 1895; Lebleu 1869; Plocq 1873). A schematic evolution of the waterways, the fairway and the port basins given on Figure 6 illustrates these purposes.

Dunkirk was first mentioned in 646 when Saint Eloi had built a church in the dunes, which he called “*Dune Kercke*” meaning “the church in the dunes”. In 906 a town wall was erected to protect the city against the first invasions.

Under the reign of the Counts of Flanders in the 11th century the harbor of Dunkirk established itself more and more, the primary activity was herring fishing. The first human alterations on the intertidal zone were made in the 13th century when the first fascine fence jetties were built to delimit and to foster the deepening of the fairway by using river flow and tidal forces. During the 16th century the harbor consisted of a 450 m quay and jetties reaching 350 m out into the sea.

The beginning of the 17th century saw the implementation of important channels, either to drain the wetlands or to install navigation between Dunkirk and the cities in the hinterland. Sluices helped maintain high water levels for navigation. During the “*Battle of the Dunes*” in 1658 the Spanish lost Dunkirk to the English and French, but Louis XIV was able to redeem the city and its surroundings a few years later. At the end of the 17th century, under the reign of the Sun King, Vauban transformed the city into a stronghold by raising new fortifications and improving the harbor's infrastructure. The jetties of the fairway entrance at the seaside were extended and prolonged to 1200 m and in total six forts were built on the intertidal zone. The marine deck was excavated, maintained by masonry quays and the arsenal implemented. Regulating the discharge of the sluices helped with desilting and digging of the inner deck that allowed big vessels to enter.

Philip, Duke of Anjou, grandson of the king of Spain Charles II and grandson of Louis XIV inherited the Spanish Empire in 1700. The war of the Spanish succession began, as the other European rulers reformed the great Alliance, as they were dissatisfied about the legacy of Spain. The treaty of Utrecht ended this war in 1713, which was disastrous for the city of Dunkirk as it stipulated that “*The most Christian King shall take care that all the fortifications of the city of Dunkirk be razed, that the harbor be filled up, and that the sluices or moles which serve to cleanse the harbor be levelled, and that at the said King's own expence, within the space of five months after the conditions of peace are concluded and signed; that is to say, the fortifications towards the sea, within the space of two months, and those towards the land, together with the said banks, within three months; on this express condition also, that the said fortifications, harbor, moles, or sluices, be never repaired again. All which shall not, however, be begun to be ruined, till after that everything is put into his Christian Majesty's hands, which is to be given him, instead thereof, of as an equivalent*” (Wikisource 2017). As the re-negotiation of this

article failed, the city of Dunkirk was almost entirely ruined and in 1714 a cofferdam was erected to completely cut off the harbor from its access to the sea.

In 1720 this cofferdam was destroyed during a storm with its associated waves, and Dunkirk's inhabitants used this opportunity to redress the port infrastructure and the jetties were rebuilt using the construction stones of the destroyed fortresses in the intertidal zone.

A few decades later, as a consequence of the treaty of Aix-la-Chapelle (1748) it was stipulated that "*Dunkirk shall remain fortified on the Side of the Land in the same condition as it is at present; and as to the Side of the Sea, it shall remain on the Footing of Former treaties*". English commissioners supervised the destruction of the fortresses on the seaward side. Nevertheless, in the 1750s a new channel, the Cunette channel was built throughout the old fortifications around the eastern part of the city which flew in the fairway channel via a new sluice. Louis XV allocated an important sum to the recovery of the port infrastructures: sluices were fixed; the marine deck was restored as well as the docks on the city side that were built either in woodwork or masonry. The Paris treaty in 1763 which ended the Seven Years' War between the French and Great Britain meant again significant destruction of the port: the marine deck and its sluice, the Cunette channel and its sluice were annihilated; incisions were made in the jetties on the sea-side allowing the sand to fill in the fairway. Only the channel of Furnes and Bergues and their respective sluices, Kesteloot and Bergues, were maintained.

It was the treaty of Versailles in 1783 that finally freed Dunkirk from the British and the Utrecht treaty. The reconstruction of Dunkirk and its harbor began, with special decrees according funding during the end of the 18th century and throughout the 19th century. The main restorations were dedicated to the strengthening of the quays surrounding the inner harbor and the fairway. Distribution channels and the associated sluices for the inland waters were either built, such as the Cunette channel on the eastern side of the city, or newly constructed, such as the derivation channel on the western side. To improve the dredging of the affluent channels and the fairway, the performances of the sluices were improved and an additional reservoir was added in the 1820s.

The railway arrived in 1838, and its rails led directly to the port. In the 1840s the inner harbor, which had thus far been a stranding port, was transformed into a wet dock by adding two sluices and the complete basins were deepened by about one meter. In 1861 a second wet dock was built and in the 1890s three more basins on the western side of the channel communicating with each other were put in service. Despite the heavy bombing of the city during the First World War, the port facilities were saved from destruction. The old fortifications were finally destroyed as they prevented the further development of the harbor during the 1920s. A new outer-harbor with a new sluice was built. At the end of the Second World War and the German occupation, the city of Dunkirk was 90% destroyed and the harbor almost annihilated. The reconstruction as well as the massive extension of the harbor area began and today the port is capable of accommodating all types of goods and the largest vessels (22m draft). It has two maritime entrances and extends for 17 km along the coast between Dunkirk and Gravelines and occupies an area of about 7000 hectares (Port Autonome de Dunkerque 2017a; Port Autonome de Dunkerque 2017b).

APPENDIX 2: EVENT RECONSTRUCTION

This section focuses on the reconstruction of the major events for the investigated time period from 1770-1846. All levels were reconstructed according to the current Dunkirk chart datum (CD), which corresponds to the Lowest Astronomical Tides (LAT) (SHOM 2017b). The Dunkirk chart datum has not evolved since 1836 (comm. Pers. A. Latapy, SHOM). Tidal predictions were estimated at the current tide gauge location. Within this study we consider the water levels at the tide gauge station to be comparable to the water levels at the different reconstruction points in the city, as (Bulteau et al. 2015) suggested.

1. 31st DECEMBER 1778

a. Data Scale

On New Year's Eve of 1778 a furious gale occurred and hit the cities of Dunkirk and Calais (Bossaut 1898). Strong west to northwesterly winds were blowing, ruining chimneys, roofs and three windmills were said to be blown away in the lower city of Calais (MA [Municipal Archives] Calais, MS169). Rough seas caused the wrecking and grounding of a dozen English ships in the Channel. In Dunkirk, consequences of the strong winds were that the waters of the sea rose up the dock shelves up to the "*Halle de l'Estran*" (literally the "*Hall of the Foreshore*") at the entrance of the Dunkirk harbor (Cailliez 1912).

b. Quantification

Total Water Level

Cunette Quay

Despite the third partial destruction of the harbor infrastructures stipulated by the treaty of Paris in 1763, the quays on the city side, that were reconstructed in the years of 1756-1759, don't seem to have been as wrecked

as a sketch drawn in 1774 indicates (Desmarets and Frazer 1774). This sketch shows also the exact location of the “*Halle de l’Estran*” and mentions that the quays along the channel and in front of the hall were rebuilt in 1773.

(Gauthier 1862) drew a map of Dunkirk which also shows the height of the different quays around the channel and the harbor of the city. In this sketch, the quay located at the location of the “*Halle de l’Estran*” is called Cunette Quay and its height is given at 6.80 m above Cunette CD which corresponds to 7.25 m. According to (Plocq 1873) the Cunette Quay was reconstructed in the 1830s.

A second sketch from the end of the 19th century, more contemporary to the event, shows the profile of woodwork quays located in front of the “*Halle de l’Estran*” (Desmarets and Frazer 1773). Reconstructing the height of this quay is tied to strong hypothesis. The estimated height of the quays is 4 feet above the “*high tide*” line according to the scale given on the sketch. The assumption was made that the metric system is given in “*royal feet*” where one foot corresponds to 0.3248 m and consists of 12 inches. (Plocq 1873) gave mean tidal levels for Dunkirk in the late 19th century; these levels are shown in table 2. Assuming that the “*high tide*” level corresponds to mean high water spring (MHWS) given by (Plocq 1873) and thus adding 4 feet, i.e. 1.30 m given on the sketch, results in a height of the quay of 6.75 m above the Cunette CD or 7.20 m. This value is consistent with the height of the Cunette Quay given on the sketch of (Gauthier 1862) from the 1860, i.e. 6.80 m above Cunette CD or 7.25 m.

The lower water levels given by (Plocq 1873) seem unrealistic. Supposing that the “*high tide*” level on the 1773 sketch would represent the Mean High Water Neaps at 4.45 m Cunette CD, the height of the quay would be 5.75 m Cunette CD, i.e. 6.10 m. This level is just slightly higher than the MHWS given at 5.45 m Cunette CD, which means that the quays would have been flooded regularly during high spring tides.

Due to the lack of precision of the type of feet and the uncertainties of interpretation of the sketch from the (Desmarets and Frazer 1774) sketch, a *A-Flag* was added to the total water level estimated at “*Halle de l’Estran*” Quay. A *T-Flag* has been added to the height of Cunette Quay, as the plan used for the reconstruction originates from more than 80 years later.

The source considered the quay to have been flooded, so the reconstructed water level is a minimum water level.

Skew surge estimation

Tidal prediction, using the R package *TideHarmonics* and a correction of sea level rise according to (Wahl et al., 2013), estimates a water level of 5.56 m the 31st December 1778 at 22h01 UTC.

The resulting minimum skew surge is 1.69 m with *T-Flag* at the Cunette Quay.

2. 2nd February 1791

a. Data Scale

In the beginning of February 1791 “extraordinary high waters”, which accompanied west- to northwesterly winds, flooded newly gained polders, areas around Calais, Dunkirk and the Belgium coastline as well as the cited cities. In Calais, the water level is said to have risen 8 inches, i.e. around 20 centimeters, higher than in 1778 (MA Calais MS169). Flooding was reported also on the Flemish Coast, where seawater is said to have provoked important dune erosion and reached the hinterland of Blankenberge, close to Zeebrugge during the night (Claerebout 1935). In Dunkirk, the sea level rose above the floodgates of the Bergues and Kesteloot sluices that were located in the most inner parts of Dunkirk harbor (Cailliez 1912; Lemaire 1857).

b. Quantification

Total Water Level

Bergues Sluice

A sketch from the MA of Dunkirk dated after the 1830, shows the height of different sluice gates in the Dunkirk harbor area. Unfortunately, no information is given regarding the Bergues sluice gate. The height of closest sluice gate is given for the Cunette sluice gate which, after reconstruction, can be given at 1.4 m above MHWS (MA Dunkirk 506). Assuming the Bergues sluice gate has the same height as the Cunette sluice gate would give a height of 6.85 m above Cunette CD, which, according to (Plocq 1873) can be transposed to 7.30 m CD.

Unfortunately, no information about the Kesteloot sluice and its gate was found and the canal de Furnes, on which the Kesteloot sluice was located, was filled in the early years of the 19th century (MA Dunkirk 1Fi256, (Derode 1852), MA Dunkirk 2Fi13 (Bottin 1811)).

City-Side Quay

Figure 7 shows a sketch from the MA dated to 1740 that shows a profile of a woodwork dock (b)) that is supposed to be transformed into a masonry quay (a)) and the location on the city-side of the harbor (d)). The

delta between the blue line and the top of the dock is estimated at 3.3 feet, i.e. 1.1 m, considering the measurement unit is given in royal feet.

Making the hypothesis that the blue line corresponds to the MHWS according to (Plocq 1873) and adding the delta of 1.1 m gives a total height of the City-Side quay of 6.55 m above Cunette CD, i.e. 7 m above CD. This value is lower than height of the Hollandais Quay given on the sketch of (Gauthier 1862) from the 1860, i.e. 7.19 m above Cunette CD or 7.64 m.

The source considered the quay to have been flooded, so the reconstructed water level is a minimum water level a Δ -Flag was added, as the uncertainty remains (i) whether the blue line corresponds to MHWS or not and (ii) whether the construction project was carried out in the exact way. Secondly, as there is a spatial and temporal inconsistency of the time and date given in the event description and the location and documents used for the reconstruction, the height was tagged with a T -Flag as well as an S -Flag.

Cunette Quay

Finally the hypothesis was made, that if the quays in the most inner part of the harbor were flooded, the quays at the harbor entrance were also flooded. The same approach as for the event of 1778 was then applied, resulting in a total water level of 7.25 m using Cunette Quay.

As there is a spatial and temporal inconsistency of the time and date given in the event description and the location and documents used for the reconstruction, the water level reconstructed using the height of the Cunette Quay was tagged with a T -Flag as well as a S -Flag.

Both estimations are minimum water levels, as the sources considered the quay or the sluice gate to have been flooded.

Skew surge estimation

Tidal prediction, using the R package *TideHarmonics* and a correction of sea level rise according to (Wahl et al., 2013), estimates a water level of 5.75 m the 2nd February at 23h39 UTC.

The resulting minimum skew surge is approximately 1.55 m, with Δ - S - T -Flags at the Bergues Sluice.

The resulting minimum skew surge is approximately 1.25 m, with Δ - S - T -Flags at the City Side Quay.

The resulting minimum skew surge is 1.50 m with T -Flag at the Cunette Quay.

3. 2nd October 1807

a. Data Scale

In the night from 1st to 2nd October 1807, in Calais, part of a jetty was reported to be carried away by the agitated seas; which in the city harbor also displaced a canon at more than hundred footsteps (De Fortia d'Urban 1808). During this “*extraordinary high tide accompanied by North-north-western winds in Dunkirk*” the sea level “*rose fifteen inches above the woodwork quay on the city side of the center*” and damaged the stone jetties at the entrance of the Dunkirk fairway (Bottin 1811).

b. Quantification

Total Water Level

Unfortunately for Dunkirk no sketches of the city quays in the early 19th century were found.

Cunette Quay

Here again, at first, the height of the Cunette Quay was used.

Assuming the fifteen inches cited by (Bottin 1811) are given in “royal foot”, 0.41 m can be added to the height of the quays given at 7.25 m, the total water level reached is 7.66 m chart datum.

Considering the metric system given in “foot of Flanders”, which according to (Doursther 1840) consists of 10 inches and corresponds to 0.2753 m, 0.41 m can be added to the height of the quays, resulting in 7.66 m.

City-Side Quay

A second estimation was made using the height of the city-side quay from 1740. Adding fifteen “royal foot” inches to the height of the quay, gives a total water level of 7.41 m.

Considering the metric system given in “foot of Flanders”, 0.41 m can be added to the height of the quay, resulting in 7.41 m total water level.

As hypotheses on the metric system were made (Royal Foot or Foot of Flanders) and spatial and temporal hypothesis were made, the Δ , S and T Flag were added.

The source considered the quay to have been exceeded by fifteen inches, the reconstructed water level is considered as an approximate water level.

Skew surge estimation

Tidal prediction, using the R package *TideHarmonics* and a correction of sea level rise according to (Wahl et al., 2013), estimates a water level of 6.26 m the 1st October 1807 at 23h29 UTC.

The resulting minimum skew surge is 1.40 m with Δ - S - T - $Flags$ using the Cunette Quay when using Royal Foot or Foot of Flanders.

The resulting skew surge is around 1.15 m, with Δ - S - T - $Flags$ at the City Side Quay when using Royal Foot or Foot of Flanders.

4. 15th February 1808

a. Data Scale

The storm occurred during the night of 14th to 15th January. Strong gales from a north-west to northerly direction coinciding with high tide caused extraordinary water levels on the Flemish Coast, and reports of marine flooding are found from Calais to the Dutch coasts, where all Zeeland and especially the Walchern Island were flooded in a horrendous way. In this area waters are said to have risen up to 20 feet (no precision of metric system is given) causing the death of 200 people and most of the cattle (Journal Politique de Mannheim 1808). Similar descriptions are given for the Escaut estuaries where polders dedicated to agriculture were submerged. The author relates that there hasn't been an event as catastrophic as this inundation since 1531 (Journal du Commerce de Politique et de Littérature du Département de l'Escaut 1808). In Gravelines, located approximately 20 km westwards of Dunkirk, water levels were reported to be one and one a third meter above normal in the harbor (MA Dunkirk 5S429, MA Gravelines 3Fi 6, (Leducq and Alexandre 1814)). For Dunkirk cellars are reported to be flooded and the force of the tide and waves nearly destroyed both fortresses located on either side of the fairway in the intertidal zone. It is related that the water level rose “34 inches above the woodwork quay on the city side of the center” (Bottin 1811).

b. Quantification

Total Water Level

Cunette Quay

Assuming the 34 inches cited by (Bottin 1811) are given in “royal foot”, i.e. 0.92 m can be added to the height of the quay given at 7.25 m, the total water level reached is 8.17 m chart datum.

Considering the metric system given in “foot of Flanders”, which according to (Doursther 1840) consists of 10 inches and corresponds to 0.2753 m, 0.92 m can be added to the height of the quays, resulting in 8.17 m.

City-Side Quay

The height of the city-side quay from 1740 was used, i.e. 7 m. Adding 34 “royal foot” inches, i.e. 0.92 m, to the height of the quay, gives a total water level of 7.92 m.

Considering the metric system given in “foot of Flanders”, 0.92 m can be added to the height of the quay, resulting in 7.92 m total water level.

As hypotheses on metric system were made (Royal Foot or Foot of Flanders) and spatial and temporal hypotheses were made, the Δ , S and T Flag were added.

The source considered the quay to have been exceeded by 34 inches, the reconstructed water level can be considered as an approximate water level.

Skew surge estimation

Tidal prediction, using the R package *TideHarmonics* and a correction of sea level rise according to (Wahl et al., 2013), estimates a water level of 5.89 m the 15th January 1808 at 00h35 UTC.

The resulting minimum skew surge is 2.28 m with Δ - S - T - $Flags$ using the Cunette Quay when using Royal Foot or Foot of Flanders.

The resulting skew surge is around 2.03 m, with Δ - S - T - $Flags$ at the City Side Quay when using Royal Foot or Foot of Flanders.

5. 4th February 1825

a. Data Scale

The storm lasting from the 3rd - 4th February is also known as the “*Halligflut*” in the German Bight. During this event the Frisian Islands, as well as the coastline and the Elbe riverbanks up to Hamburg were massively flooded. The severity of this event is due to the coincidence with the high tide, as the winds weren’t as severe as during previous events. The surge above MHWs is estimated at 3.55 m in Hamburg reaching even 4.01 m in Husum on the North Frisian shoreline. The sources relate the death of about 800 people and 45000 cattle (Meier 2012). The extension of the storm reaches from Boulogne in Northern France up to the Danish Coast. Strong winds were blowing gale force from a south-westerly direction on the 2nd of February, reaching their maximum during the night of 3rd to 4th February from a north-westerly direction (Lamb and Frydendahl 1991). For the French most northern cities the consequences of the high waters were similar causing fewer casualties: the quays around the harbors were flooded in Dunkirk, Calais and Boulogne. The high tide is said to have risen due to strong winds blowing from a north-westerly direction in Calais (MA Dunkirk 50 6, (Lemaire 1857)).

b. Quantification

Total Water Level

Cunette Quay

As for previous events, the assumption was made that the quays at the end of the channel were flooded and a minimum water level for the 1825 event results in 7.25 m at the Cunette Quay.

City-Side Quay

As for previous events, the reconstructed height of the city side quay from 1740, which is given at 7 m, was used for the estimation of a total water level.

The sketches used for the reconstruction are not contemporary to the event, and assumptions on the location were made, therefor the *S* and *T-Flag* were added.

Both estimations are minimum water levels, as the sources considered the quay to have been flooded.

Skew Surge Estimation

Tidal prediction, using the R package *TideHarmonics* and a correction of sea level rise according to (Wahl et al., 2013), estimates a water level of 5.89 m the 4th February 1825 at 00h05 UTC.

The resulting minimum skew surge is 1.36 m using the Cunette Quay with *S* and *T-Flags*.

The resulting minimum skew surge is 1.11 m, with *A-S-T-Flags* at the City Side Quay.

6. 2nd January and 2nd October 1846

a. Data Scale

(Derode 1852) lists more than 30 events, during which some high water levels are supposed to have caused damages to the shorelines and some flooded the hinterlands. While for almost all events only the year of occurrence is given in years, two of these events are given with complete date and complementary information. “in 1846, January 2nd the sea level exceeded 51 centimeters and October 2nd it exceeded 41 centimeters the top of the woodwork quay on the city side” (Derode 1852). No information is given about the location in Dunkirk and (Derode, 1852) is the only source for these two events.

b. Quantification

Total Water Level

Cunette Quay and Hollandais Quay

According to (Plocq 1873) the Cunette Quay and the “*Quai des Hollandais*” (Hollandais Quay - Quay of the Dutch) were reconstructed in the late 1830s.

Following the sketch of 1860 by (Gauthier 1862), the aforementioned quays are the lowest and highest quays in Dunkirk harbor and their heights are given at 6.80 m and 7.19 m respectively above the chart datum of the Cunette sluice. Translating these values into the current chart datum gives a lowest and highest quay height of 7.25 m and 7.64 m, respectively.

For the event of January 1846, 51 cm were added to the quay height, resulting in reached water levels of 7.76 m at the Cunette Quay and 8.15 m at the Hollandais Quay.

In the beginning of October 1846, the quays were exceeded by 0.41 cm, resulting in a total water level of 7.66 m at the Cunette Quay and 8.05 m at the Hollandais Quay.

Skew surge estimation

No hourly precision is given for these two events. Tidal predictions are made using the R package *TideHarmonics* and a correction of sea level rise according to (Wahl et al., 2013).

Tidal prediction estimates a water level of 6.00 m the 2nd January 1846 at 02h23 UTC.

Tidal prediction estimates a water level of 6.01 m the 2nd January 1846 at 15h07 UTC.

The resulting minimum skew surge is 1.76 m, with *S-T-Flags* for the morning tide at the Cunette Quay.
The resulting minimum skew surge is 1.75 m, with *S-T-Flags* for the evening tide at the Cunette Quay.
The resulting minimum skew surge is 2.15 m, with *S-T-Flags* for the morning tide at the Hollandais Quay.
The resulting minimum skew surge is 2.14 m, with *S-T-Flags* for the evening tide at the Hollandais Quay.

Tidal prediction estimates a water level of 5.43 m the 2nd October 1846 at 09h27 UTC.
Tidal prediction estimates a water level of 5.78 m the 2nd October 1846 at 21h55 UTC.

The resulting minimum skew surge is 2.23 m, with *S-T-Flags* for the morning tide at the Cunette Quay.
The resulting minimum skew surge is 1.88 m, with *S-T-Flags* for the evening tide at the Cunette Quay.
The resulting minimum skew surge is 2.62 m, with *S-T-Flags* for the morning tide at the Hollandais Quay.
The resulting minimum skew surge is 2.27 m, with *S-T-Flags* for the evening tide at the Hollandais Quay.

c. Comments

It was not possible to crosscheck these events in national or international storm data bases (Daubord et al. 2015; Haigh et al. 2017; Lamb and Frydendahl 1991; Lang et al. 2016; Météo France 2018); (Derode 1852) is so far the only source and the information is only found in a footnote. Water levels reached are estimated at around 8 m above CD, which corresponds to the water levels reached during the storm of 1953 (Le Gorgeu and Guitonneau 1954) which caused inundations and damage in the city in the surroundings; no damages reports were found for the events of 1846.

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Figure 1: Location of Dunkirk in the Northern Part of France.

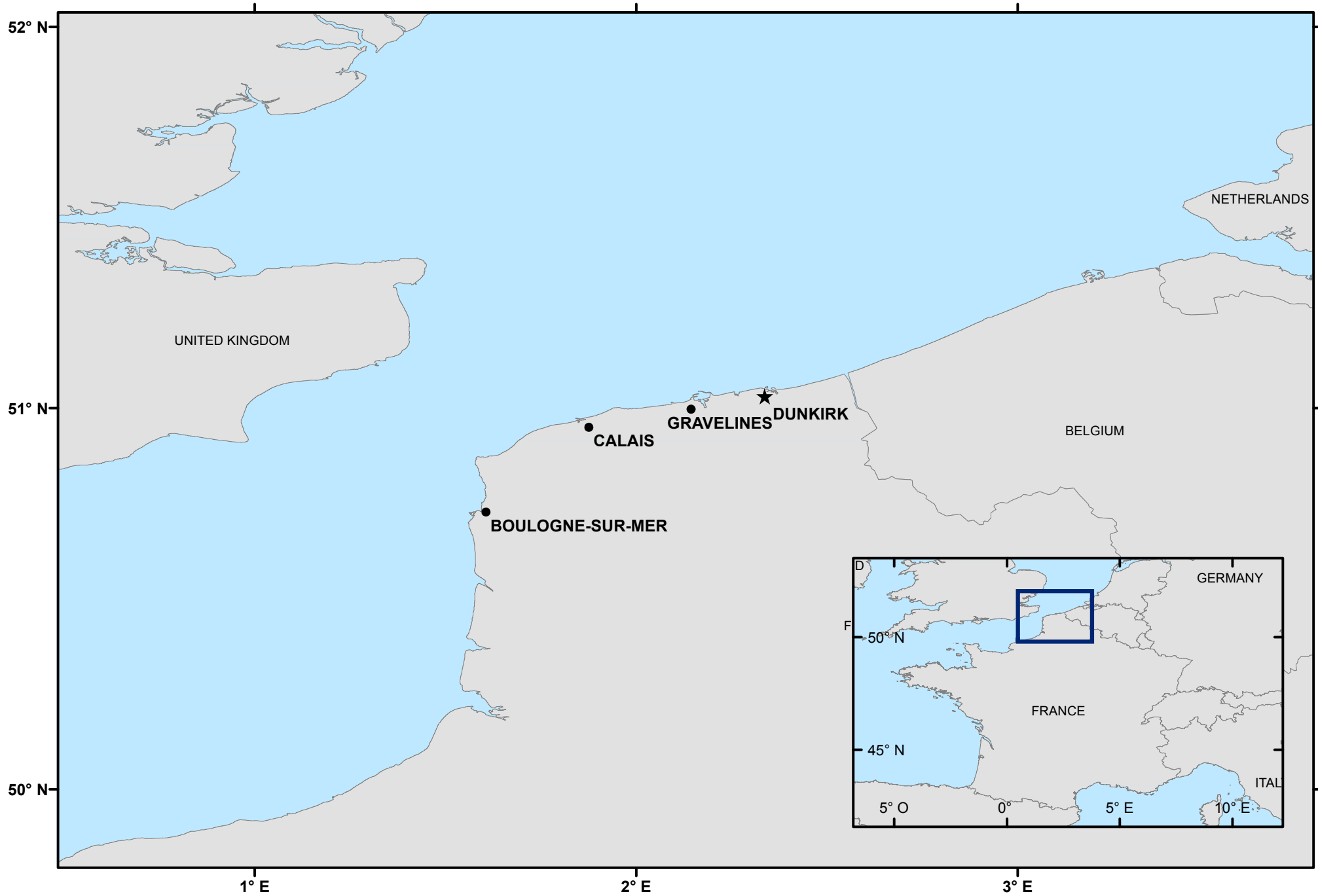


Figure 2: Timeline of historic floodings (events where flooding is mentioned) and storms (events where no indication of flooding is given) in the study area (Hamdi et al., 2017 in

[Click here to access/download;Figure;Figure_2.eps](#) 

Timeline of Storm and Flooding events

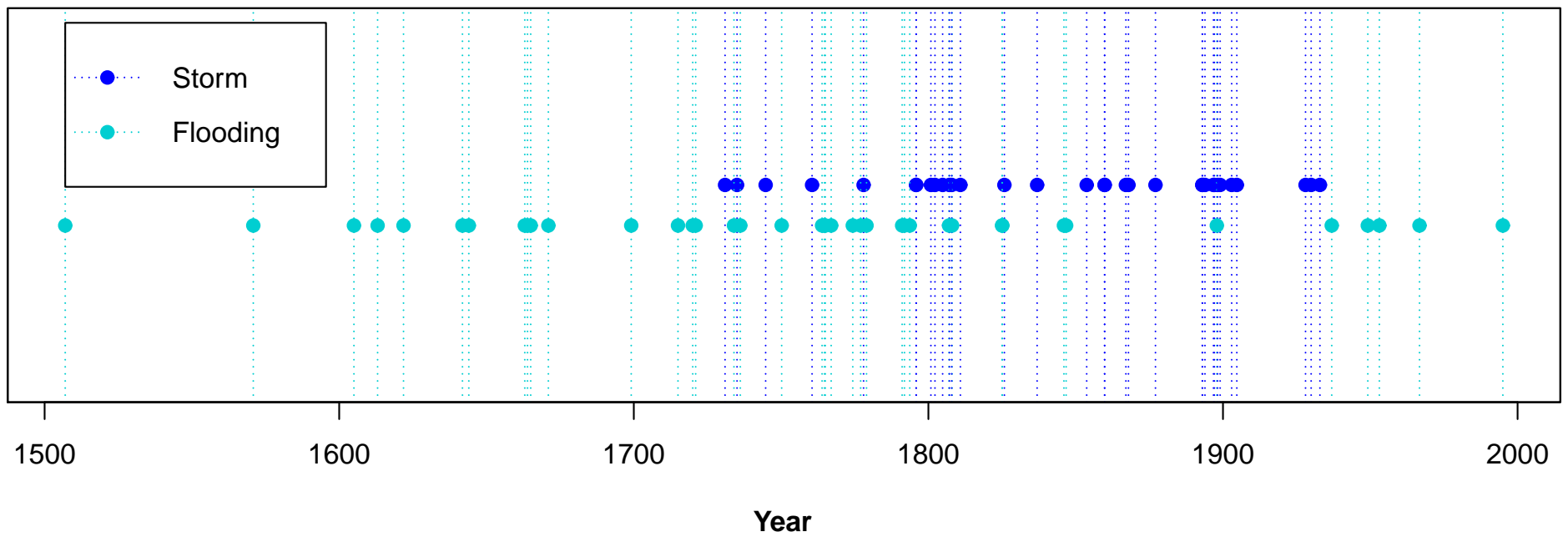


Figure 3: Approach used for the reconstruction of historic levels.

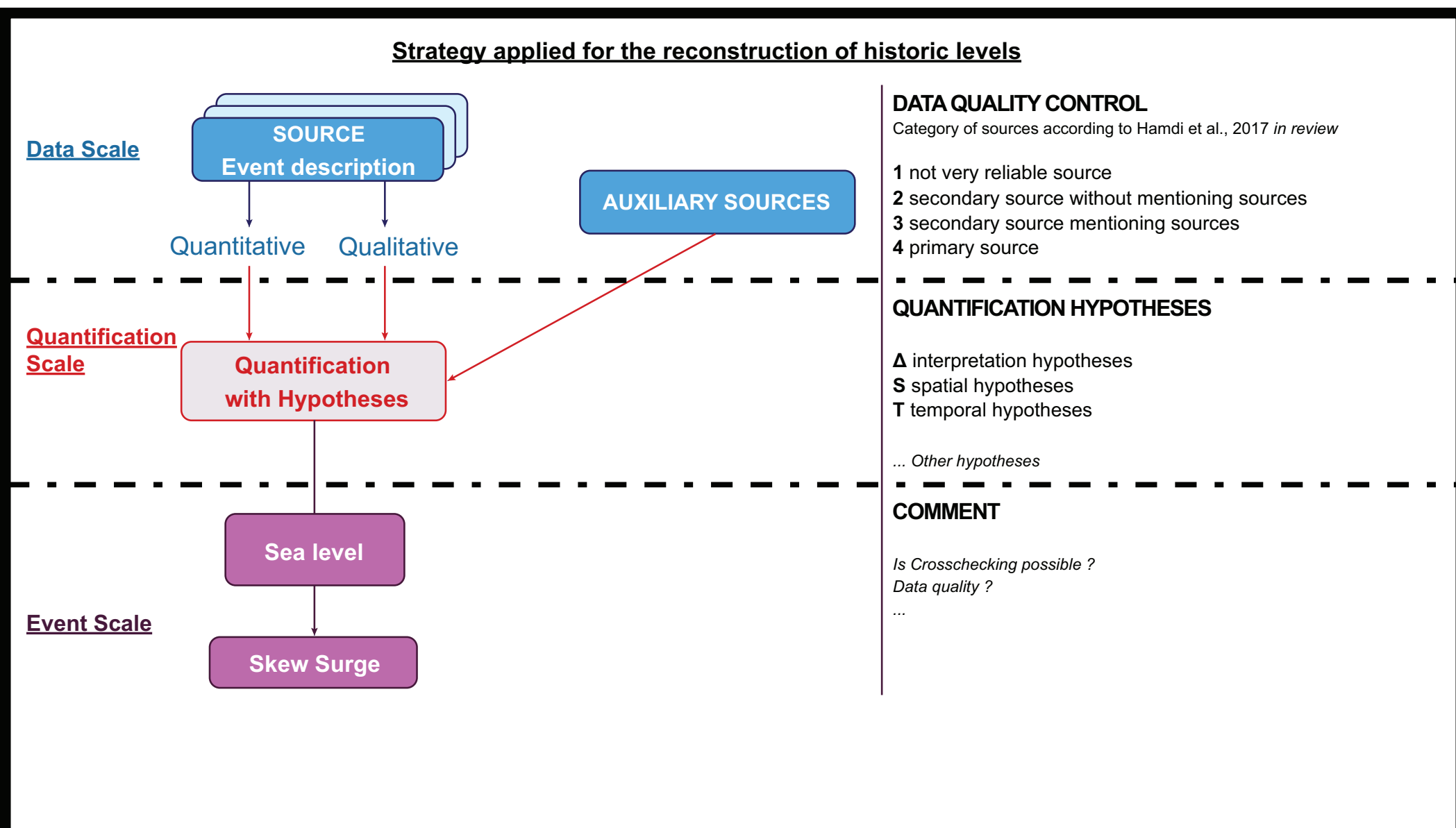


Figure 4: Location of points where water level reconstructions were made in the center of Dunkirk.

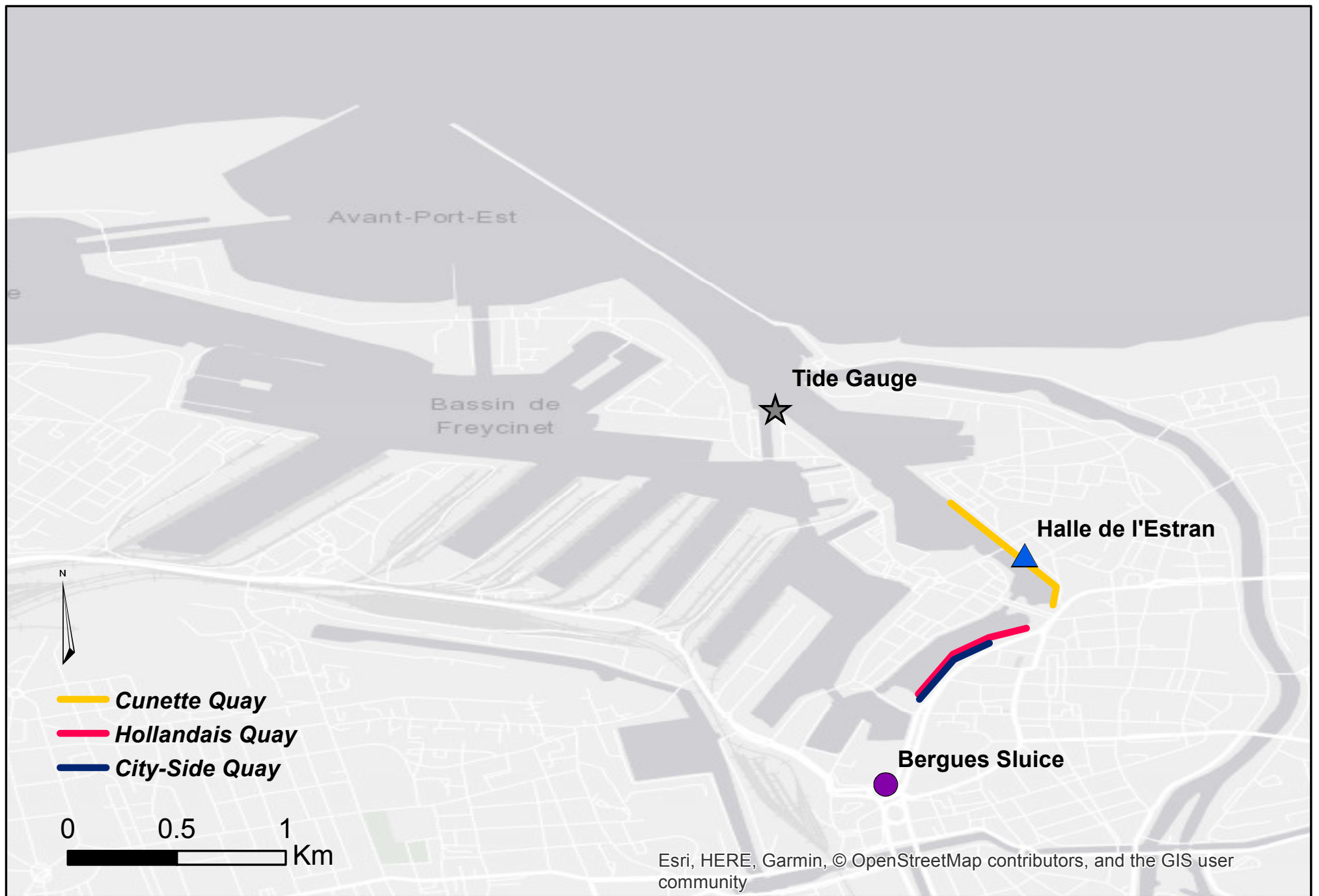


Figure 5: Skew surge estimated using the tide gauge data, data from the literature (1897: (Nord-Pas-de-Calais 2009), 1949 and

[Click here to access/download;Figure;Figure_5.eps](#)

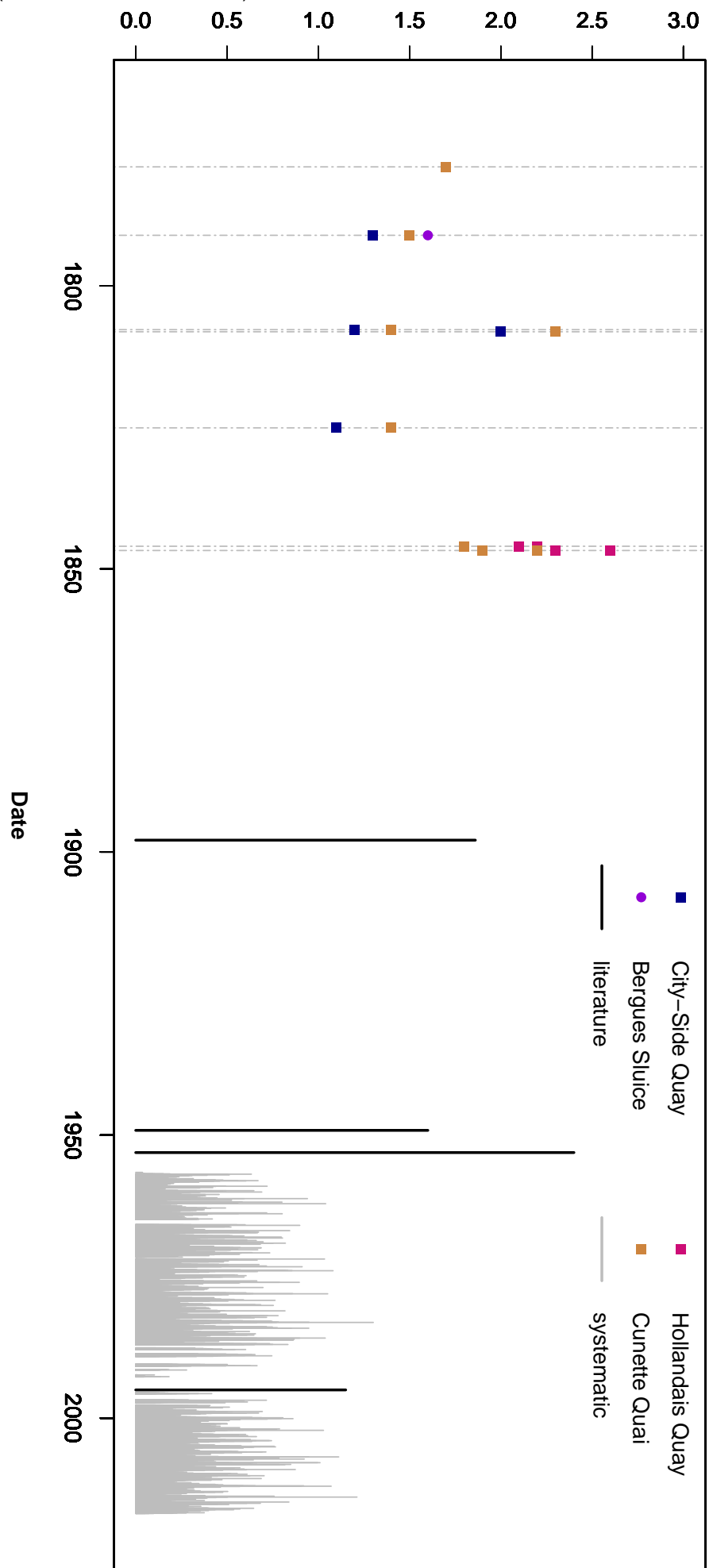


Figure 6: Evolution of the Dunkirk Harbor and waterways from the 18th century to today.

[Click here to access/download;Figure;Figure_6.eps](#)

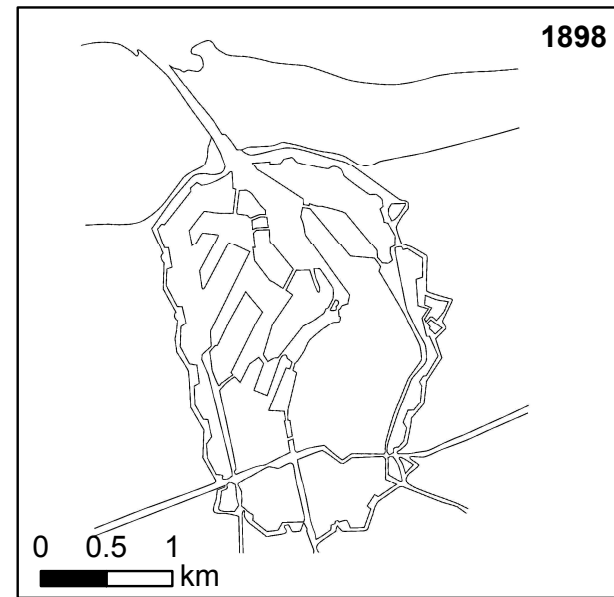
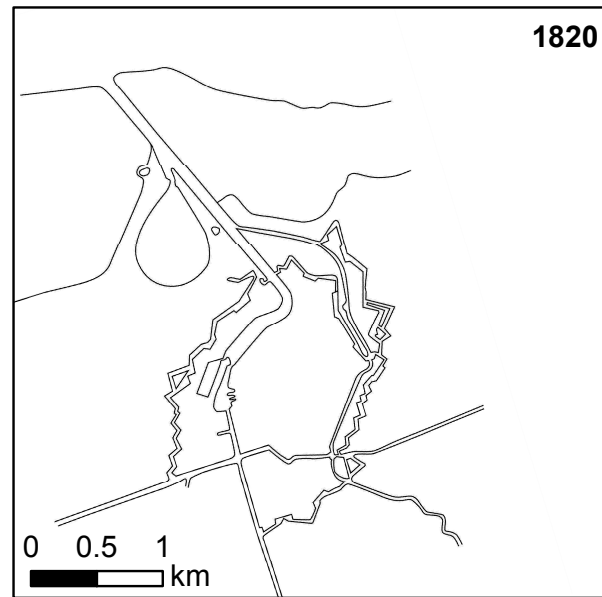
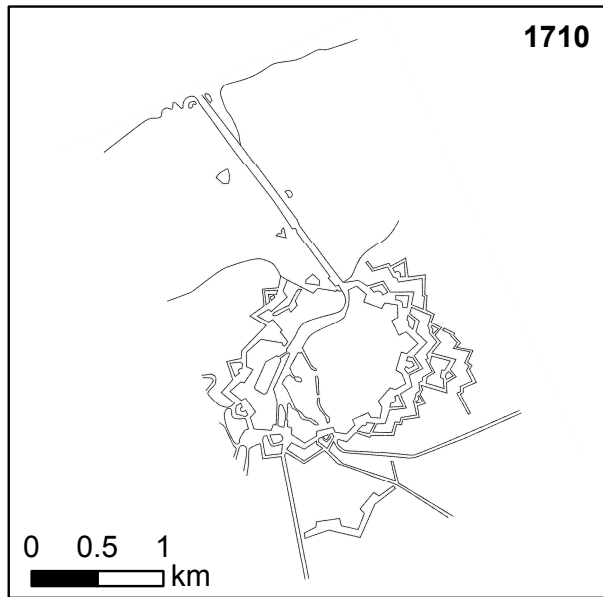


Figure 7: Sketch from 1740 showing a) a profile of the construction project of a masonry quay (upper left corner), b) the current

[Click here to access/download/Figure;Figure_7.eps](#)

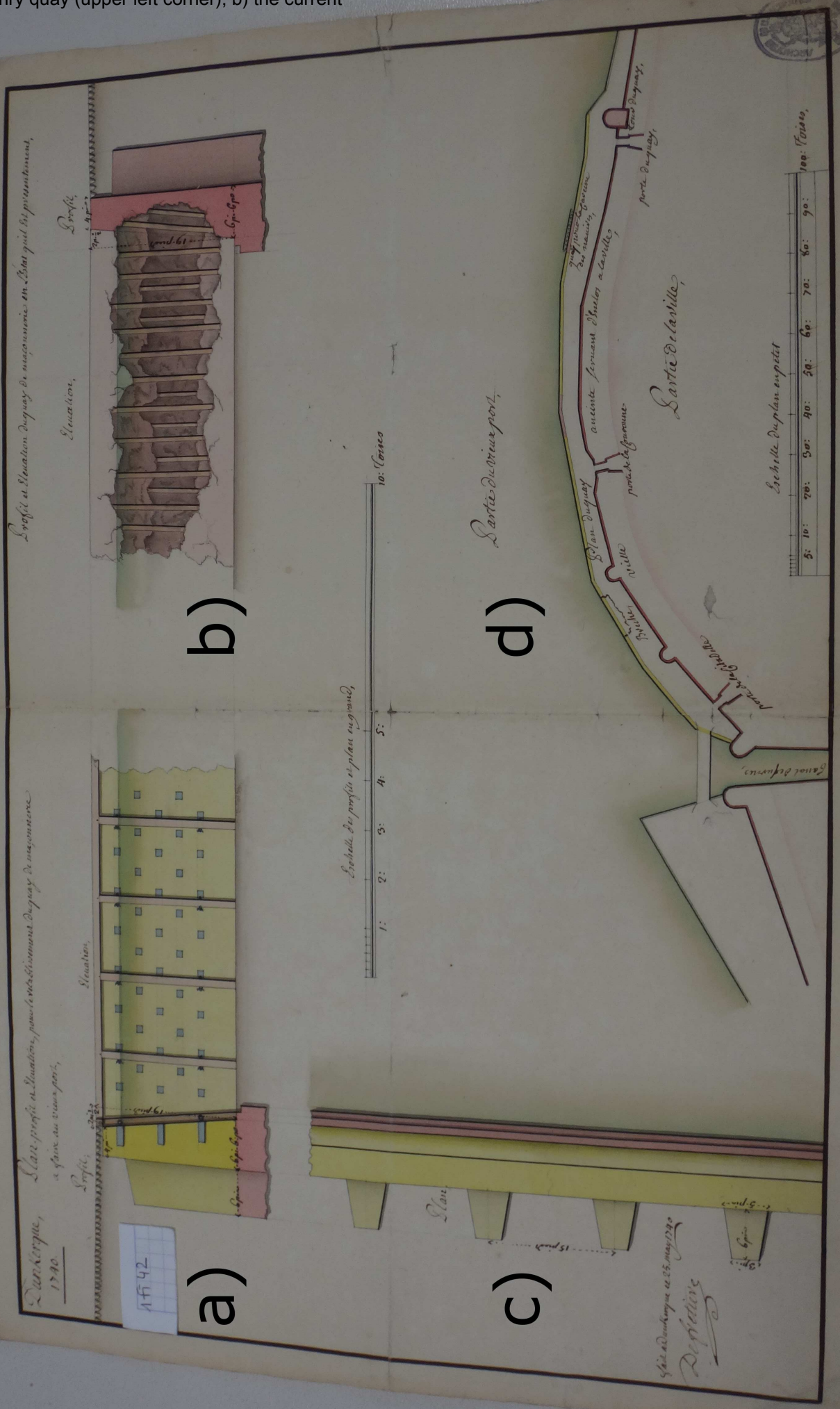


Table 1: Reconstructed water levels, associated flags and skew surges. RF: reconstruction using royal feet. FF: reconstruction using feet of Flanders. m = morning tide, e = evening tide. Details are given in the Appendix.

date	Data Quality [number of sources x category]	TWL [m 0 chart datum]	Hypotheses	Comment	Skew surge [m]	Reconstruction Location in Dunkirk
1778-12-31	4 x c3	≈ 7.3	T		≈ 1.7	<i>Cunette Quay</i>
1791-02-02	5 x c3	≈ 7.3	ST		≈ 1.5	<i>Cunette Quay</i>
		≈ 7.3	ST		≈ 1.6	<i>Bergues Sluice</i>
		≈ 7.0	Δ ST		≈ 1.3	<i>City-side quay 1740</i>
1807-10-02	1 x c4 1 x c3	≈ 7.7	ST		≈ 1.4	<i>Cunette Quay RF</i>
		≈ 7.6	ST		≈ 1.4	<i>Cunette Quay FF</i>
		≈ 7.4	Δ ST		≈ 1.2	<i>City-side quay 1740 RF</i>
		≈ 7.4	Δ ST		≈ 1.2	<i>City-side quay 1740 FF</i>
1808-02-15	2 x c4 4 x c3	≈ 8.2	ST		≈ 2.3	<i>Cunette Quay RF</i>
		≈ 8.2	ST		≈ 2.3	<i>Cunette Quay FF</i>
		≈ 7.9	Δ ST		≈ 2.0	<i>City-side quay 1740 RF</i>
		≈ 7.9	Δ ST		≈ 2.0	<i>City-side quay 1740 FF</i>
1825-02-04	2 x c4 3 x c3	≈ 7.3	ST		≈ 1.4	<i>Cunette Quay</i>
		≈ 7.0	ST		≈ 1.1	<i>City-side quay 1740</i>
1846-01-02	1 x c3	≈ 7.8	ST	no crosschecking /	$\approx 1.8m / 1.8e$	<i>Cunette Quay</i>
		≈ 8.2	ST	high water levels	$\approx 2.2m / 2.1e$	<i>Hollandais Quay</i>
1846-10-02	1 x c3	≈ 7.7	ST	no crosschecking /	$\approx 2.3m / 1.9e$	<i>Cunette Quay</i>
		≈ 8.1	ST	high water levels	$\approx 2.6m / 2.3e$	<i>Hollandais Quay</i>

Table 2 : Mean Water Levels given by (Plocq 1873) according to two chart data.

Water level	In [m above Cunette chart datum]	In [m above chart datum]
Highest Astronomical Tides	6.7	7.15
Mean High Water Springs	5.45	5.90
Mean High Water Neaps	4.45	4.90
Mean Sea Level	2.75	3.20
Mean Low Water Neaps	1.25	1.70
Mean Low Water Springs	0	0.45
Lowest Astronomical Tides	-0.45	0

Point by point response – Reviewer #2

Reviewer	Authors
<p>The rearrangement of this paper has substantially improved it and made it more appropriate for Natural Hazards. The treatment of the tides is better, the figures hugely improved. It is very localised, but that is a decision for the editor. However for the results of the paper to be useful to any other study they must address the handling of uncertainty, which remains non-standard at best.</p>	<p>Thank you for your remarks.</p> <p>It was shown in the literature (see the last paragraph of the discussion and (Ouarda et al. 1998; Salas et al. 1994; Stedinger and Baker 1987) that historical information improve significantly the frequency estimations of extreme events, even if they are uncertain. Therefore, the aim of this paper is to show that reconstruction is possible, not to assess the associated uncertainties.</p> <p>Still, we modified our approach for the reconstruction of the events of 1778 – 1825 which for the site “Cunette quay” allows us to remove the Delta flag. Instead of using the height reconstructed using the sketch of 1773 (uncertainties about MHWS, transposition of feet into meters...) we decided to use the sketch from 1860 – where the height of the quay is already given in meters. A. Latapy, PhD candidate from SHOM confirmed that since 1836 the Dunkirk Chart Datum has not changed. Still, for informative purposes, a <i>T</i> and <i>S</i> (where necessary) <i>Flag</i> was added because the sketch used for the reconstruction is not contemporary to the event and / or it was not specified which quay in the city was flooded.</p>
<p>This is illustrated by the statement (now in the appendix) that "approximately 4 royal feet" + MHWS leads to 6.75m (with no error bar). It's simply wrong, and misleading, and the "uncertainty flag" is not enough to bury it.</p>	<p>See above.</p>
<p>The flags and approx symbols in Table 1 are not helpful, especially as most of them apply to most cases... the only case not flagged Delta as a measurement error is the one flagged as Dubious? So there's no unflagged data?</p>	<p>As said above, the reconstruction method was modified, and the flags adapted. We also removed the D-Flag, which had a negative connotation and renamed the last step “General Comment”, to keep the analysis more neutral. We do not want to judge, we want to set the focus one or more points of attention for further use of the data.</p> <p>Unfortunately in this study, there is no unflagged data, because in most cases, the sources (i) did not give the exact location of the flooding and (ii) it was difficult to find auxiliary sources which are contemporary to the selected events. Still, even if the value is flagged, is it still valuable information e.g. for policy makers and for statistical purposes.</p>

<p>"Whereas in 1953 massive flooding and dyke destruction is reported, Derode 1852 reports no damage, except the high water level." I do not follow this logic when so many factors have changed. And relying on the absence of evidence to dismiss data you are sceptical of seems problematic.</p>	<p>We do not want to dismiss the reconstructed heights of 1846. We tried to crosscheck this event with other national data bases (Daubord et al. 2015; Lang et al. 2016; Météo France 2018; Roche et al. 2014) or even in international bases such as (Haigh et al. 2017; Lamb and Frydendahl 1991) for example, but unfortunately we found no other evidence for these two events. Instead of tagging it with the D-flag, we added a comment addressed to potential users, to underline that besides the hypothesis associated to the reconstruction, there is an interrogation concerning the events themselves (no crosschecking possible, high water and surge levels).</p>
<p>I suggest that rather than simply flagging the uncertainties, the authors assess the likely errors and carry them through the calculations. Don't forget to check the errors on MHWS as well. It is more work, but this would make the results in the paper usable for future studies, and without it they are meaningless.</p>	<p>See above.</p>
<p>The English is much improved, but there remain a large number of minor grammatical points and incorrect usages, and the paper should be proof-read for English by a native speaker.</p>	<p>The paper has been proof-read in order to improve the English.</p>

Point by point response – Reviewer #3

Reviewer	Authors
<p>I feel this is an interesting paper illustrating the use of rescued data, but that minor revisions are needed before it should be published. The paper fits with the scope of the journal and although other researchers are carrying out similar work, I feel this paper is worth publishing as it focuses on an interesting region historically that has not been discussed before.</p>	<p>---</p>
<p>I would have liked to have seen further demonstration about the impact of the various stages of dredging and development on the harmonic constituents in the region. This could have been done by analysing the available tide gauge data. The Permanent Service for Mean Sea Level (PSMSL) has data from 1942-2017 which would suggest that high frequency data may be available and could be analysed to see if the harmonics had changed over 75 years. Copies of tide gauge charts for Dunkirk are available as early as 1941 (beginning 1st March 1941) so it is unclear which gauge was operational in 1956</p>	<p>The tide gauge data available on the French data portal for maritime data https://data.shom.fr/ spans from 1956-today, unfortunately we don't have access to the earlier data. During previous studies we made an analysis of harmonics, of this dataset, but no significant change was found for the last sixty years. The biggest evolution of the harbor area has been undertaken at the end of the 19th century, when the four new docks were built from scratch on dune and maritime territories. It is therefore difficult to evaluate the evolution of the harmonic constituents during this time.</p> <p>There is a PhD-Thesis on in progress directed by Nicolas Pouvreau (SHOM) and Arnaud Hequette (Dunkerque University): Alexa Latapy is analyzing historic bathymetric charts and digitalizing historic tide gauge data. This work could give more information about the evolution on local hydrodynamics around Dunkirk during the past 150 years. More information on this work can be found here: Refmar website</p>
<p>I would like to see a statement in the conclusion that discusses the limitations of the method, in terms of the accuracy of the results. This could be based on the results displayed in Table 1, where the quality of the source and the "hypotheses" employed for each event are listed. I would be wary of comparing data from a historic source with modern instrumental data, as the two methods are not commensurate. Historic data are very valuable, but by their nature they will always only give estimations of surge, or minimum values of height, where quays have been overtopped etc.</p>	<p>Thank you for this remark. We added a paragraph at the end of the discussion which should make it clearer for the reader, that we are aware of the limitations of this method.</p>
<p>I have uploaded a version of the pdf file that includes my suggestions for minor corrections of the text. The 65 comments/suggestions should be viewable in Acrobat if the comments list is</p>	<p>Thank you for this file, the comments and corrections were very helpful for this revision. Figure 3 was improved and we removed the one reference from the reference list.</p>

displayed. There was one reference listed that wasn't referenced in the main text (Maspataud 2011). Figure 3 was blurred when printed and other figures would benefit from extra labels on axes or improved titles.	
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