Modelling dependence and coincidence of storm surges and high tide: Methodology and simplified case study in Le Havre (France)

Amine Ben Daoued 1, Yasser Hamdi 2, Nassima Mouhous-Voyneau 1, Philippe Sergent 3

1 Sorbonne University, Université de Technologie de Compiègne, 60203 Compiègne, France
2 Institute for Radiological Protection and Nuclear Safety, 92 262 Fontenay-Aux-Roses, France
3 Centre d’étude et d’expertise sur les risques, l’environnement, la mobilité et l’aménagement, France

Correspondence to: Y. Hamdi (yasser.hamdi@irsn.fr)

Abstract. Coastal facilities such as nuclear power plants (NPPs) have to be designed to withstand extreme weather conditions and must, in particular, be protected against coastal floods because it is the most important source of coastal lowlands inundations. Indeed, considering the combination of tide and extreme storm surges (SSs) is a key issue in the evaluation of the risk associated to coastal flooding hazard. Tide and extreme SSs are considered as independent. While there are several approaches to analyze and characterize coastal flooding hazard with either extreme SSs or sea levels, only few studies propose and compare several approaches combining the tide density with the SS variable. Thus this study aims to develop a method for modelling dependence and coincidence of SSs and high tide. In this work, we have used existing methods for tide and SS combination and tried to improve the results by proposing a new alternative approach while showing the limitations and advantages of each method. The city of Le Havre in France was used as a case study. Overall, the example has shown that the return levels estimates using different combinations are quite different. It has also been suggested that the questions of coincidence and dependency are essential for a combined tide and SS hazard analysis.

Key-words: Coastal flooding, Combination, Joint Probability Method, Convolution, Dependence, Coincidence

1. Introduction

More than 80% of electricity in France is derived from nuclear energy. Like any other urban facilities, Nuclear Power Plants (NPPs) can be subject to external influences and aggressions such as extreme environmental events (river and/or marine flooding, heat spells, etc.). Both nuclear and urban facilities have to be designed to withstand extreme weather conditions. Five NPPs are located on the Atlantic coast (including the Channel). During the last few decades, France has experienced several violent storms (the great storm of 1987, Lothar and Martin cyclone in 1999, Klaus in 2009 and Xynthia in 2010) that gave rise to exceptional SSs. The Blayais NPP was partially flooded when storm Martin struck the French coast in 1999. A combination of an exceptional SS, of a high tide and high waves (induced by strong winds) led to the overflow of the dikes. According to Mattéi et al. (2001), the dikes were not designed for such a concomitance of events. A guide to protection, including some fundamental changes in the assessment of flood risks, has therefore been produced by the Nuclear Safety Authority (ASN, 2013). However, to be conservative, approaches used in the guide are deterministic which do not take into account all the local specificities of each site. The safety demonstration and protections and are periodically reviewed to ensure compliance with the increased safety requirements. The present work could be used to enrich safety verification approaches. To supplement knowledge which can be acquired from the deterministic method, the probabilistic approach has been identified as an effective tool for assessing risk associated with hazards as well as for estimating uncertainties.
The first probabilistic study in the nuclear safety field was conducted in the United States in 1975 (US-NRC, 1975). This report focused on estimating the probability of occurrence of meltdown accidents with associated radiological consequences. Currently, probabilistic approaches are applied in several fields such as medicine, chemical industry, insurance and aeronautics. Many studies have already been conducted for the seismic hazard (IAEA, 1993; Beauval, 2003; Gupta, 2007), the tsunami hazard (IRSN, 2015), and other climatic hazards such as tornadoes (US-NRC, 2007). There are not many probabilistic studies yet in the fields of climate and hydrometeorology, as it is an approach barely used. In fact, very few researches and developments are explicitly referred by their authors as conclusive and operational. Probabilistic Flood Hazard Assessment (PFHA) is identified by Bensi and Kanney (2015) as a first step in a Probabilistic Risk Assessment (PRA). According to the authors, it is an evaluation of the probabilities that one or more parameters representing the severity of the external flood (water level, duration, and associated effects) are exceeded in a site of interest. Also, the authors discuss the Joint Probability Method (JPM) as an alternative to existing deterministic and statistical methods such as the Empirical Simulation Technique (EST). Kügel (2013) proposed a methodology for characterizing the external flood hazard in the case of a river nuclear sites and the articulation of this Hazard study with a flooding Probabilistic Safety Assessment (PSA).

It is a common belief today that the probability of failure (The probability of exceeding an extreme event) over an infrastructure lifetime is one of the most important pieces of information an engineer can communicate. The estimation of this probability should be based on the combination of all flood phenomena (e.g. Pluvial, fluvial and marine floods) which are most often dependent because they are induced by the same storm. For example, extreme SSs are often accompanied by rains in coastal areas. Mostly, a flood phenomenon can be characterized by several explanatory variables, some of which are correlated. For example, river floods can be described not only by its peak, but also by other characteristics such as its volume and duration. An intense rainfall event is characterized by its intensity and its duration, the correlation of which is not usually negligible. On the other hand, there are some phenomena which are described by other explanatory phenomena. The case of multi-components phenomena that will receive our attention in the present paper is the marine flooding which is a combination the tide (which can be predicted) with a SS. Indeed, the SS is the main driver of coastal flood events. It is an abnormal rise of water generated by a storm (low atmospheric pressure and strong winds), over and above the predicted tide. Extreme storms can produce high sea levels, especially when they coincide with high tide. The SSS is a sea level component which is often considered as the fundamental input (the quantity of interest) for statistical investigations of coastal hazards. It is the difference between the highest observed level and the highest predicted one, for a same high tide. These maximum levels can occur at slightly different times.

Numerous studies have shown that, in case of multivariate hazards, a univariate frequency analysis does not allow to estimate in a complete way the probability of occurrence of an extreme event (Chebana and Ouarda, 2011; Hamdi et al., 2016). According to Salvadori and De Mechele (2004), modelling the dependency allows a better understanding of the hazard and avoids under/over-estimating the risk. Unsurprisingly, some ideas have been proposed in the literature for combining tides and SSs and to help address such an important issue. JPM is an indirect method that made an improvement in addressing the main limitations of the direct methods (e.g. the annual maxima method (AMM) and the r-largest method (RLM)) (Haigh et al., 2010). Several studies refer to the JPM for the probabilistic characterization of storms (Batstone et al., 2013; Haigh et al., 2010; Pugh and Vassie, 1978; USACE, 2015). Tawn and Vassie (1989) proposed a Revised JPM (RJPM) in which the distribution of
surges is composed by a left tail defined by an empirical method and a right tail defined by frequency analysis. Dixon and Tawn (1994) made some modifications on the RJPM and proposed a new model to take into account the interaction between instantaneous SS and tide. Recently, Haigh and al. (2010) showed the advantages of indirect methods (i.e. JPM, RJPM) compared to direct ones (i.e. AMM and RLM). More recently, Kergadallan et al. (2014) undertook the method of Dixon and Tawn (1994) using skew storm surges (SSSs) to compare several methods. Some other studies have been proposed in the literature to tackle the PFHA. The most important contribution proposes two methods. The first estimates extreme sea levels (ESLs) with the JPM (Pugh and Vassie, 1980). Indeed, this approach combines separated frequency distributions for the tide (usually deterministic and exact) and the SS (frequency analysis based on the extreme value theory). It is a calculation of the convolution based on the tidal levels density function and of a distribution function of SSs (Duluc et al., 2012) have shown that the quality of the results from this convolution approach for small return periods is questionable. The second procedure uses the data of observed maximum water levels (Chen et al., 2014; Haigh et al., 2014; Huang et al., 2008). This approach was recommended by FEMA’s guideline (FEMA, 2004) for coastal flood mapping. The GEV model was recommended to conduct the frequency analysis of extreme water levels, if long-term datasets are available. Based on the regional observations, the process of estimation of extreme water levels uses an adequate frequency analysis model to estimate the distribution parameters, the desired return levels (RLs) and associated confidence intervals.

Overall, our goal is to build on the approaches and developments proposed in the literature and revive the debate as to how researchers and engineers can combine tide with SS to estimate extreme sea levels. This goal is in line with the recent literature (e.g. Idier et al., 2012) challenging the use of the SSS and clearly demonstrates the importance of conducting extreme value analyses with maximum instantaneous ones. In order to achieve this goal, a third fitting procedure to estimate extreme sea levels using the maximum SS (MSS) between two consecutive tides is introduced with an application so that it can be compared with the two first procedures.

The paper is organized as follows. The section 2 takes up the two fitting procedures proposed in the literature (the JPM with a convolution between tides and SSSs and the frequency analysis directly on sea levels) and proposes a new one based on the convolution between tides and MSSs. In section 3, the fitting procedures are applied on the observed and predicted sea levels at the Le Havre tide gauge in France used as a case study. Some theoretical basis for the multivariate analysis using copulas will be addressed.

2. Methods

Tide and SSs are usually the subject of a statistical study to determine the probability of exceeding the water level cumulating the two phenomena. Indeed, the SS is the main driver of coastal flood events. It is an abnormal rise of water generated by a storm, over and above the predicted tide. Unlike to what is done very often in the literature, the question of dependency is not essential at all to combine phenomena in the present work. Indeed, as mentioned in the introductory section, tidal signals and SSs are independent. On the other hand, it is commonly known today that the tidal signals can be predicted, and are not aleatory like the SSs. What is somewhat odd in the present work is that one thus seeks to combine a distribution function (random phenomenon) with a density of tide (deterministic). In order to estimate extreme sea levels, a JPM is used by making use of a convolution between tide and SSs. So the question that arises here is which variable of interest represents the SSs? Three variables are then...
proposed: (i) the SSS; (ii) the MSS and (iii) the extreme sea level. The theoretical basis for the fitting procedures using these variables is addressed in the following subsections.

Relative to some chosen datum, each hourly observed sea level \( Z(t) \), may be considered as the sum of its tide \( X(t) \) and storm surge component \( Y(t) \), i.e.:

\[
Z(t) = X(t) + Y(t)
\]

(1)

Thus if the probability density functions of the tidal and surge components are \( f_X(x) \) and \( f_Y(y) \) respectively then the probability density function \( f(z) \) of \( z \), under the assumption that the tide and surge components are independent, is:

\[
f_z(z) = \int_{-\infty}^{\infty} f_X(x) \times f_Y(z-x) f_z(z) \, dx
\]

(2)

As it can be seen in equation 2, the dependence on time, \( t \), is omitted when replacing \( X(t) \) by \( X \), \( Y(t) \) by \( Y \) and \( Z(t) \) by \( Z \). This implies a stationarity assumption for the involved time series. The hourly theoretical tide signal is often considered as a stationary stochastic process, but this is not the case of the hourly SSs since SS meteorological and seasonal effects give rise to series of SSs not randomly distributed in time.

2.1 Joint SSS - tide probabilistic method

This method is based on the decomposition of the sea level into a sum of two contributions: the tide which is evaluated theoretically and the SS (aleatory component) obtained by subtracting the predicted tide from the observed sea level. Extreme storms can produce high sea levels, especially when it occurs simultaneously with high tide. The SSS is a sea level component which is often considered as the fundamental input for statistical investigations of coastal hazards. It is calculated between two maximums (observed-predicted) and is not impacted by the shift of the two signals which may be biased (see figure 1). As shown in the left panel of figure 2, the SSS is defined herein as the difference between the highest observed level and the highest predicted one, for a same high tide (see equations 1 and 2). Further noteworthy features of SSs are its occurrence with a high tide. Indeed, a SSS occurring with a high tide is more likely to induce a high sea level than an instantaneous SS occurring with any other tide. Thus, for safety requirements, SSS is the most often used in the literature Kergadallan et al. (2014). Still, even if this procedure uses the suitable variable of interest, it has its limitations. Indeed, it is not uncommon that the MSS, which can occur randomly somewhere between two consecutive tides, is greater than the SSS. Widening the window around the high tide, in which extreme SSs are extracted, could improve frequency estimation of extreme sea levels. When this window is maximum (12 hours, for instance), the variable of interest naturally becomes the MSS. Moreover, it was demonstrated in the literature that the tide and SSS interaction at high tide cannot be neglected (Kergadallan et al., 2014).

2.2 Joint MSS - tide probabilistic method

The right panel of figure 2 illustrates the case of an instantaneous SS signal, the variables would be the MSS and the high tide \( M_{nM} \). As mentioned in the previous section, the MSS can occur randomly somewhere in a tide cycle. One of the most important features of MSS is that it is more informative than the SSS. Indeed, the MSS covers the
whole instantaneous SS signal. This feature makes the MSS a variable particularly useful for carrying out a PFHA exploring the entire tidal signal, not only the high tide.

2.3 Inference with the ESL: the reference method

For comparison purposes, we also analyzed sea levels signals for which we focused our attention on the frequency analysis on extreme sea levels without decomposing them into tides and surges. This yields to direct statistics and estimates of the RLs without combining tides and surges. The intent of this analysis is only to illustrate and obtain results that can serve as a reference for the comparison of the joint probability procedures. As it can also be noticed for this reference procedure, the variable of interest would be the maximum sea level between 2 high-tide values.

3 Case study and data

The city of Le Havre is an urban city in the Seine-Maritime department, on the English Channel coast in Normandy (France). It is a major French city located in northwestern France. A map showing the location of the Le Havre city in France can be found in figure 3. The name Le Havre means "the harbour" or "the port". The port of Le Havre is, moreover, among the largest in France. For these reasons, the city of Le Havre remains deeply influenced by its maritime traditions.

Due to its location on the coast of the Channel, the climate of Le Havre is temperate oceanic. Days without wind are rare. There are maritime influences throughout the year. According to the meteorological records, precipitation is distributed throughout the year, with a maximum in autumn and winter. The months of June and July are marked by some relatively extreme storms on average 2 days per month. One of the characteristics of the region is the high variability of the temperature, even during the day. The prevailing winds are from north-northeast for breezes and, from the southwest sector for strong winds.

The joint tide-surge probability and the frequency analysis of extreme sea levels are performed on the city of Le Havre. The 1971-2015 observed and predicted sea levels recorded at the port of Le Havre were provided by the French Oceanographic Service (SHOM - Service Hydrographique et Océanographique de la Marine). One of the most important features of the Le Havre (as a case study) is the fact that Le Havre is a city subject to marine submersions and instabilities of coastal cliffs (Elineau et al., 2013; Elineau et al., 2010; Maspataud et al., 2016). In particular, the lower part of the city (Saint-François district, for instance) is likely to be flooded by marine and pluvial floods. Data characteristics are shown in the table 1. These data were first processed to keep only common periods containing a minimum of gaps. The choice of the variables to be probabilized is done at this stage.

4. Results

All the simulations were carried out within the R environment (open source software for statistical computing: http://www.r-project.org/). The SeaLev library (developed by the French Institute for Radiological Protection and Nuclear Safety - IRSN) was used for the standard approach involving the convolution of the probability density functions of the tidal and surge heights to obtain the distribution of total sea levels. It is the same package that was
used by Duluc et al., (2012). The frequency analyses were performed with the Renext library also developed by IRSN (IRSN and Alpstat, 2013). The Renext package was specifically developed for flood frequency analyses using the Peaks-Over-Threshold (POT) method.

Since we need to get comparable annual rates of extreme sea level events, the POT threshold selection process has been adapted to meet this criterion and the thresholds are, even though, checked regarding the stability graphs of the GPD parameters estimated with the maximum likelihood method. The main results of the joint surge-tide probability method (with the SSS and MSS based fitting procedures) and the results of the frequency analysis of the extreme sea levels (3rd procedure) as well, with all the diagnostics are presented in terms of RL plots, estimates of the quantiles of interest and associated 95% confidence intervals. In these results, the main focus was set to the 10-, 50-, 100- and 1000-year storm surge RLs. Prior to the application of the JPM, the SSSs and MSSs are calculated first from observed and predicted sea levels. The results of the application on the Le Havre are summarized in table 2 and presented in figure 4.

The RL estimates obtained with the MSS based convolution are quite different from those of the one based on SSSs. The results of the calculation of confidence intervals (with the delta method) are presented with transparent polygons in figure 4 and in table 2 as well. As it can be noticed, the confidence intervals are relatively narrow. Indeed, the relative width of these intervals did not exceed 12% (around the 1000-year RL obtained with reference method). Better yet, the confidence intervals are narrower when using the joint probability procedures.

Furthermore, it can be seen in figure 4 that for a given RL, the return period given by the MSSs-based procedure is much lower than that given by the one based on the SSSs. The RLs are thus more frequently (i.e. on average 10 times more frequently) exceeded randomly in a tidal cycle (i.e. as the MSS can occur randomly somewhere inside a tidal cycle) than at the high tide moment (i.e. if we suppose that SSS often occurs at the high tide moment).

It is noteworthy that the shape parameter $\xi$ of the General Pareto Distribution (GPD) is negative for all the cases (i.e. $\xi = -0.2$; $\xi = -0.07$ and $\xi = -0.12$ for the SSS, MSS and ESL based fitting procedures, respectively). This parameter governs the tail behavior of the GPD. The right tail of the distribution is much heavier for the procedures using SSSs and the ESLs than for the one using MSSs.

5 Discussion

To objectively evaluate the merits and shortcomings of each of the methods described in section 2, the assumptions made in developing them must be analyzed first. The JPM is developed under assumption of independence between the tidal signal and both SSS and MSS on one side and independence of extreme hourly sea levels on the other side. Tawn and Vassie (1989) found that the latest assumption was false. Considering that the tide and the surge are independent is an assumption that may be true under certain circumstances as proved by William et al. (2016) for the largest mid-latitude storm surges and the corresponding tide. A tendency to overestimate sea levels because of the correlation in the hourly SSSs has been ignored was recognized in the literature (Pugh and Vassie, 1978, 1980; Walden et al., 1982). However, it should be noticed that extreme levels such as the MSSs may be only very weakly dependent. This constitutes a distinctive feature and advantage of the MSS based fitting procedure introduced in the present paper. It is a major point of differentiation between the joint surge-tide probability procedures described in sections 2. Furthermore, the hourly theoretical tides are in utmost
cases considered as a realization of stationary stochastic process. This assumption is the most critical one since sea
levels are highly non-stationary (due to the tide). As previously argued to overcome this limitation, the variability
arises from the SSs (since SS meteorological and seasonal effects lead to SS series which are not randomly
distributed in time and as most high tides are similar in term of their value) which can be considered as stationary
over the storm season for instance. For this argument to be less subjective, most high tides are similar in term of
their value and must be lower than the SS variation in extreme events.

The question one can ask is how to improve the modelling in such a way that the bias between the procedures
using SSSs and MSSs and the reference one is reduced as far as possible? Indeed, as depicted in figure 4, the
second procedure overestimates extreme sea levels for all the return periods (a maximizing envelope). The RLs
estimates for MSS based procedure are about 50 to 60 cm higher than those obtained when the SSS are used. The
difference between the upper and middle curves increase as the return period goes up. The difference is high for
the low return periods. Inversely, the difference between the lower and middle curves increase as the return period
goes down. The difference is significant for the major return periods. It is noteworthy that the middle curve is
supposed to represent the RLs of reference. An objective answer to our question cannot in any case suggest a
modification in the reference method. Two methodological issues could provide us with solutions and answers to
the question. First, the dependence structure that exists between the extreme instantaneous SSs around the high
tide could be modelled. Extreme SSs one hour before the high tide, at the time of the high tide and one hour after
can be used. A larger window can likewise be used to consider the SSs around the high tide in a multivariate
context.

Multivariate frequency analysis consists in studying the dependence structure of two or more variables through a
function that depends on their marginal (univariate) distribution functions. The multivariate theory is based on the
mathematical concept of copula (Sklar, 1959), which allows linking the distributions of the variables according to
their degree of dependence. More details can be found in (Salvadori and De Michele, 2004; Nelsen, 2006). A
copula-based approach may be used to study the dependence of instantaneous SSs (or sea levels). In the case of a
copula of sea levels, no convolution is needed. The convolution of a copula of SSs with a density of tide permits to
obtain a copula of sea levels. This first solution is proposed herein as an alternative to the first procedure fitting
using the SSSs.

Second, we believe that a bias is introduced with the MSS based procedure because it does not take into account
the time difference between the maximum instantaneous SS and the high tide. A probability of coincidence (i.e.
the chance that a MSS occurs at the same time with high tide) can be used to better characterize the extreme sea
levels using the MSS. An appropriate coincidence probability concept would then allow to better estimate the
probabilities and thus reduce the bias and bring the RLs closer to those obtained by the reference method.

As shown in the right panel of figure 2 the MSS can occur randomly somewhere around the high tide $M_n$. The
time difference between the MSS and the high tide is random as well. One can introduce an additional random
variable to describe this temporal difference $\Delta t$. Then a coincidence probability concept can be drawn as follows:

- Extract an independent sample of $\Delta t$
- Fit this sample with the POT method
Choose a RL of $\mathcal{D}$ (100-year RL, for instance) and use its probability to weight the probabilities of the MSSs (i.e. assuming that MSSs and $\Delta S$ are independent).

It is noteworthy that $\mathcal{D}$ is a random variable and therefore it is quite legitimate to study it with a frequency analysis method as the MSS.

Furthermore, figure 4 shows that extreme sea level events (the right tail of the distribution: the middle curve) tend to occur at the time of the high tide, as expected. The results of this procedure confirm the general finding highlighted in the literature (Duluc et al., 2012) that the return level estimations obtained with the convolution tide-SSS are not adapted up to a certain return period (100 years in the case of Le Havre). To overcome this problem, one can use an empirical method to define the left tail of the distribution and an extreme values analysis for the right tail as stated by Tawn and Vassie (1989).

6. Conclusions

In the present paper, we provided detailed reasoning for the need, in a PFHA framework, to combine flood phenomena to avoid over or under estimations of extreme water levels. Few ideas have been proposed in the literature to tackle the combination of tidal signals with extreme SSSs to estimate extreme sea levels. The present work supports these ideas, takes up the tidal signals and SSSs convolution procedure and proposes a new procedure based on the MSSs useful to exploit likewise the extreme SS events occurred during medium and low tide hours. Three fitting procedures have been investigated. The first one employs the SSS as an explanatory variable with the tidal signals which are combined with a JPM using a convolution of the tide density and the SSS distribution function. The second procedure uses the same technique except that the MSSs are used instead of the SSSs. In the third approach, a frequency analysis is performed using ESLs.

Another consideration in this paper was applying and illustrating these approaches on the example of the sea levels in Le Havre, northwestern France, over the period 1971–2015. It may be noted that the methodology is not exemplary developed for this case study; it applies to any site likely to experience a marine flooding.

Fitting results in term of probability plots and extrapolated RLs using the three approaches are examined. Overall, the application has shown that the RL estimates for MSS based convolution are quite different from those corresponding to the SSS based one. It has also been suggested that the questions of coincidence and dependency are essential for a combined tide and SS hazard analysis. Indeed, as shown in figure 4, the results of the second fitting procedure are likely to contain a bias (comparing to the direct statistics on ESLs) which becomes more and more important as return periods increase. In order to reduce this bias, the coincidence probability concept (i.e. defined in this paper as the chance that a maximum SS occurs at the same time with high tide) can be helpful in making a more appropriate assessment of the risk (associated to ESLs) using the MSS. On the other hand and if the second procedure is to be used, the application has shown the utility of modelling the dependence structure that exists between the hourly SS values around the high tide (high tide 3 hours). Figure 4 shows that ESL events (the upper tail of the distribution: the middle curve) tend to occur at the time of the high tide, as expected. The results of this procedure confirm the general finding highlighted in the literature is that the RL estimations obtained with the convolution tide-SSS are not conclusive up to a certain return period (100 years in the case of Le Havre).
Perspective: An in-depth study could help to thoroughly improve the proposed procedure based on the use of MSS by developing the concept of coincidence and apply the developed concept on other sites of interest. A concept of coincidence and methodology to be developed should find additional applications for the assessment of risk associated to other combining flooding phenomena (e.g. pluvial flooding and storm surges).

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**Table 1: Sea level and rainfall data sets**

| Type      | Station                        | Period       | Time step |
|-----------|--------------------------------|--------------|-----------|
| Sea level | Harbour                        | 1938-2017    | 1h        |
| Rainfall  | Harbour/Perret/Cap-de-la-Heve   | 1997-2005    | 1h        |
| Rainfall  | Cap-de-la-Heve                 | 2005-2018    | 6’        |
| Method                | T=10       | T=50       | T=100      | T=1000     |
|-----------------------|------------|------------|------------|------------|
| JPM-SSS               | 8.31 (8.27-8.35) | 8.77 (8.72-8.82) | 8.89 (8.84-8.95) | 9.20 (9.07-9.32) |
| JPM-MSS               | 8.84 (8.79-8.89) | 9.29 (9.22-9.36) | 9.42 (9.33-9.51) | 9.79 (9.58-10.01) |
| Frequency Analysis - ESL | 8.82 (8.74-8.91) | 8.99 (8.80-9.18) | 9.05 (8.79-9.31) | 9.22 (8.67-9.77) |
Figure 1: Definition and schematic representation of a skew storm surge
Figure 2: Illustration of tide and storm surge signals for the joint surge-tide probability procedures: (left) skew surge-tide combination; (right) maximum surge-tide combination.
Figure 3: Case study (Le Havre): location map
Figure 4: Sea level quantiles and confidence intervals