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

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

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

21 ## 1. Introduction

22 More than 80% of electricity in France is derived from nuclear energy. Like any other urban facilities, Nuclear
23 Power Plants (NPPs) can be subject to external influences and aggressions such as extreme environmental events
24 (river and/or marine flooding, heat spells, etc.). Both nuclear and urban facilities have to be designed to withstand
25 extreme weather conditions. Five NPPs are located on the Atlantic coast (including the Channel). During the last
26 few decades, France has experienced several violent storms (the great storm of 1987, Lothar and Martin cyclone in
27 1999, Klaus in 2009 and Xynthia in 2010) that gave rise to exceptional SSs. The Blayais NPP was partially
28 flooded when storm Martin struck the French coast in 1999. A combination of an exceptional SS, of a high tide
29 and high waves (induced by strong winds) led to the overflow of the dikes. According to Mattéi et al. (2001), the
30 dikes were not designed for such a concomitance of events. A guide to protection, including some fundamental
31 changes in the assessment of flood risks, has therefore been produced by the Nuclear Safety Authority (ASN,
32 2013). However, to be conservative, approaches used in the guide are deterministic which do not take into account
33 all the local specificities of each site. The safety demonstration and protections and are periodically reviewed to
34 ensure compliance with the increased safety requirements. The present work could be used to enrich safety
35 verification approaches. To supplement knowledge which can be acquired from the deterministic method, the
36 probabilistic approach has been identified as an effective tool for assessing risk associated with hazards as well as
37 for estimating uncertainties.

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38   The first probabilistic study in the nuclear safety field was conducted in the United States in 1975 (US-NRC,
39   1975). This report focused on estimating the probability of occurrence of meltdown accidents with associated
40   radiological consequences. Currently, probabilistic approaches are applied in several fields such as medicine,
41   chemical industry, insurance and aeronautics. Many studies have already been conducted for the seismic hazard
42   (IAEA, 1993; Beauval, 2003; Gupta, 2007), the tsunami hazard (IRSN, 2015), and other climatic hazards such as
43   tornadoes (US-NRC, 2007). There are not many probabilistic studies yet in the fields of climate and
44   hydrometeorology, as it is an approach barely used. In fact, very few researches and developments are explicitly
45   referred by their authors as conclusive and operational. Probabilistic Flood Hazard Assessment (PFHA) is
46   identified by Bensi and Kanney (2015) as a first step in a Probabilistic Risk Assessment (PRA). According to the
47   authors, it is an evaluation of the probabilities that one or more parameters representing the severity of the external
48   flood (water level, duration, and associated effects) are exceeded in a site of interest. Also, the authors discuss the
49   Joint Probability Method (JPM) as an alternative to existing deterministic and statistical methods such as the
50   Empirical Simulation Technique (EST). Kügel (2013) proposed a methodology for characterizing the external
51   flood hazard in the case of a river nuclear sites and the articulation of this Hazard study with a flooding
52   Probabilistic Safety Assessment (PSA).

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

69   Numerous studies have shown that, in case of multivariate hazards, a univariate frequency analysis does not allow
70   to estimate in a complete way the probability of occurrence of an extreme event (Chebana and Ouarda, 2011;
71   Hamdi et al., 2016). According to Salvadori and De Mechele (2004), modelling the dependency allows a better
72   understanding of the hazard and avoids under/over-estimating the risk. Unsurprisingly, some ideas have been
73   proposed in the literature for combining tides and SSs and to help address such an important issue. JPM is an
74   indirect method that made an improvement in addressing the main limitations of the direct methods (e.g. the
75   annual maxima method (AMM) and the r-largest method (RLM)) (Haigh et al., 2010). Several studies refer to the
76   JPM for the probabilistic characterization of storms (Batstone et al., 2013; Haigh et al., 2010; Pugh and Vassie,
77   1978; USACE, 2015). Tawn and Vassie (1989) proposed a Revised JPM (RJPM) in which the distribution of

78   surges is composed by a left tail defined by an empirical method and a right tail defined by frequency analysis.
79   Dixon and Tawn (1994) made some modifications on the RJPM and proposed a new model to take into account
80   the interaction between instantaneous SS and tide. Recently, Haigh and al. (2010) showed the advantages of
81   indirect methods (i.e. JPM, RJPM) compared to direct ones (i.e. AMM and RLM). More recently, Kergadallan et
82   al. (2014) undertook the method of Dixon and Tawn (1994) using skew storm surges (SSSs) to compare several
83   methods. Some other studies have been proposed in the literature to tackle the PFHA. The most important
84   contribution proposes two methods. The first estimates extreme sea levels (ESLs) with the JPM (Pugh and Vassie,
85   1980). Indeed, this approach combines separated frequency distributions for the tide (usually deterministic and
86   exact) and the SS (frequency analysis based on the extreme value theory). It is a calculation of the convolution
87   based on the tidal levels density function and of a distribution function of SSs (Duluc et al., 2012) have shown that
88   the quality of the results from this convolution approach for small return periods is questionable. The second
89   procedure uses the data of observed maximum water levels (Chen et al., 2014; Haigh et al., 2014; Huang et al.,
90   2008). This approach was recommended by FEMA's guideline (FEMA, 2004) for coastal flood mapping. The
91   GEV model was recommended to conduct the frequency analysis of extreme water levels, if long-term datasets are
92   available. Based on the regional observations, the process of estimation of extreme water levels uses an adequate
93   frequency analysis model to estimate the distribution parameters, the desired return levels (RLs) and associated
94   confidence intervals.

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

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

2. Methods

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

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116   proposed: (i) the SSS; (ii) the MSS and (iii) the extreme sea level. The theoretical basis for the fitting procedures

117   using these variables is addressed in the following subsections.

118   Relative to some chosen datum, each hourly observed sea level $Z(t)$, may be considered as the sum of its tide

119    $X(t)$ and storm surge component $Y(t)$, i.e.:

120    $$Z(t) = X(t) + Y(t) \tag{1}$$

121   Thus if the probability density functions of the tidal and surge components are $f_X(x)$ and $f_Y(y)$ respectively

122   then the probability density function $f(z)$ of z, under the assumption that the tide and surge components are

123   independent, is:

124    $$f_Z(z) = \int_{-\infty}^{+\infty} f_X(x) \times f_Y(z-x) f_Z(z) dx \tag{2}$$

125   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

126   and $Z(t)$ by Z. This implies a stationarity assumption for the involved time series. The hourly theoretical tide

127   signal is often considered as a stationary stochastic process, but this is not the case of the hourly SSs since SS

128   meteorological and seasonal effects give rise to series of SSs not randomly distributed in time.

129   **2.1 Joint SSS - tide probabilistic method**

130   This method is based on the decomposition of the sea level into a sum of two contributions: the tide which is

131   evaluated theoretically and the SS (aleatory component) obtained by subtracting the predicted tide from the

132   observed sea level. Extreme storms can produce high sea levels, especially when it occurs simultaneously with

133   high tide. The SSS is a sea level component which is often considered as the fundamental input for statistical

134   investigations of coastal hazards. It is calculated between two maximums (observed-predicted) and is not impacted

135   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

136   is defined herein as the difference between the highest observed level and the highest predicted one, for a same

137   high tide (see equations 1 and 2). Further noteworthy features of SSSs are its occurrence with a high tide. Indeed, a

138   SSS occurring with a high tide is more likely to induce a high sea level than an instantaneous SS occurring with

139   any other tide. Thus, for safety requirements, SSS is the most often used in the literature Kergadallan et al. (2014).

140   Still, even if this procedure uses the suitable variable of interest, it has its limitations. Indeed, it is not uncommon

141   that the MSS, which can occur randomly somewhere between two consecutive tides, is greater than the SSS.

142   Widening the window around the high tide, in which extreme SSs are extracted, could improve frequency

143   estimation of extreme sea levels. When this window is maximum (12 hours, for instance), the variable of interest

144   naturally becomes the MSS. Moreover, it was demonstrated in the literature that the tide and SSS interaction at

145   high tide cannot be neglected (Kergadallan et al., 2014).

146   **2.2 Joint MSS - tide probabilistic method**

147   The right panel of figure 2 illustrates the case of an instantaneous SS signal, the variables would be the MSS and

148   the high tide M_n. As mentioned in the previous section, the MSS can occur randomly somewhere in a tide cycle.

149   One of the most important features of MSS is that it is more informative than the SSS. Indeed, the MSS covers the

150   whole instantaneous SS signal. This feature makes the MSS a variable particularly useful for carrying out a PFHA

151   exploring the entire tidal signal, not only the high tide.

2.3 Inference with the ESL: the reference method

153   For comparison purposes, we also analyzed sea levels signals for which we focused our attention on the frequency

154   analysis on extreme sea levels without decomposing them into tides and surges. This yields to direct statistics and

155   estimates of the RLs without combining tides and surges. The intent of this analysis is only to illustrate and obtain

156   results that can serve as a reference for the comparison of the joint probability procedures. As it can also be

157   noticed for this reference procedure, the variable of interest would be the maximum sea level between 2 high-tide

158   values.

3 Case study and data

160   The city of Le Havre is an urban city in the Seine-Maritime department, on the English Channel coast in

161   Normandy (France). It is a major French city located in northwestern France. A map showing the location of the

162   Le Havre city in France can be found in figure 3. The name Le Havre means "the harbour" or "the port". The port

163   of Le Havre is, moreover, among the largest in France. For these reasons, the city of Le Havre remains deeply

164   influenced by its maritime traditions.

165   Due to its location on the coast of the Channel, the climate of Le Havre is temperate oceanic. Days without wind

166   are rare. There are maritime influences throughout the year. According to the meteorological records, precipitation

167   is distributed throughout the year, with a maximum in autumn and winter. The months of June and July are

168   marked by some relatively extreme storms on average 2 days per month. One of the characteristics of the region is

169   the high variability of the temperature, even during the day. The prevailing winds are from north-northeast for

170   breezes and, from the southwest sector for strong winds.

171   The joint tide-surge probability and the frequency analysis of extreme sea levels are performed on the city of Le

172   Havre. The 1971-2015 observed and predicted sea levels recorded at the port of Le Havre were provided by the

173   French Oceanographic Service (SHOM - Service Hydrographique et Océanographique de la Marine). One of the

174   most important features of the Le Havre (as a case study) is the fact that Le Havre is a city subject to marine

175   submersions and instabilities of coastal cliffs (Elineau et al., 2013; Elineau et al., 2010; Maspataud et al., 2016).

176   In particular, the lower part of the city (Saint-François district, for instance) is likely to be flooded by marine and

177   pluvial floods. Data characteristics are shown in the table 1. These data were first processed to keep only common

178   periods containing a minimum of gaps. The choice of the variables to be probabilized is done at this stage.

4. Results

180   All the simulations were carried out within the R environment (open source software for statistical computing:

181   http://www.r-project.org/). The SeaLev library (developed by the French Institute for Radiological Protection and

182   Nuclear Safety - IRSN) was used for the standard approach involving the convolution of the probability density

183   functions of the tidal and surge heights to obtain the distribution of total sea levels. It is the same package that was

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184   used by Duluc et al., (2012). The frequency analyses were performed with the Renext library also developed by
185   IRSN (IRSN and Alpstat, 2013). The Renext package was specifically developed for flood frequency analyses
186   using the Peaks-Over-Threshold (POT) method.

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

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

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

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

5 Discussion

210   To objectively evaluate the merits and shortcomings of each of the methods described in section 2, the
211   assumptions made in developing them must be analyzed first. The JPM is developed under assumption of
212   independence between the tidal signal and both SSS and MSS on one side and independence of extreme hourly sea
213   levels on the other side. Tawn and Vassie (1989) found that the latest assumption was false. Considering that the
214   tide and the surge are independent is an assumption that may be true under certain circumstances as proved by
215   William et al. (2016) for the largest mid-latitude storm surges and the corresponding tide. A tendency to
216   overestimate sea levels because of the correlation in the hourly SSs has been ignored was recognized in the
217   literature (Pugh and Vassie, 1978, 1980; Walden et al., 1982). However, it should be noticed that extreme levels
218   such as the MSSs may be only very weakly dependent. This constitutes a distinctive feature and advantage of the
219   MSS based fitting procedure introduced in the present paper. It is a major point of differentiation between the joint
220   surge-tide probability procedures described in sections 2. Furthermore, the hourly theoretical tides are in utmost

221 cases considered as a realization of stationary stochastic process. This assumption is the most critical one since sea

222 levels are highly non-stationary (due to the tide). As previously argued to overcome this limitation, the variability

223 arises from the SSs (since SS meteorological and seasonal effects lead to SS series which are not randomly

224 distributed in time and as most high tides are similar in term of their value) which can be considered as stationary

225 over the storm season for instance. For this argument to be less subjective, most high tides are similar in term of

226 their value and must be lower than the SS variation in extreme events.

227 The question one can ask is how to improve the modelling in such a way that the bias between the procedures

228 using SSSs and MSSs and the reference one is reduced as far as possible? Indeed, as depicted in figure 4, the

229 second procedure overestimates extreme sea levels for all the return periods (a maximizing envelope). The RLs

230 estimates for MSS based procedure are about 50 to 60 cm higher than those obtained when the SSS are used. The

231 difference between the upper and middle curves increase as the return period goes up. The difference is high for

232 the low return periods. Inversely, the difference between the lower and middle curves increase as the return period

233 goes down. The difference is significant for the major return periods. It is noteworthy that the middle curve is

234 supposed to represent the RLs of reference. An objective answer to our question cannot in any case suggest a

235 modification in the reference method. Two methodological issues could provide us with solutions and answers to

236 the question. First, the dependence structure that exists between the extreme instantaneous SSs around the high

237 tide could be modelled. Extreme SSs one hour before the high tide, at the time of the high tide and one hour after

238 can be used. A larger window can likewise be used to consider the SSs around the high tide in a multivariate

239 context.

240 Multivariate frequency analysis consists in studying the dependence structure of two or more variables through a

241 function that depends on their marginal (univariate) distribution functions. The multivariate theory is based on the

242 mathematical concept of copula (Sklar, 1959), which allows linking the distributions of the variables according to

243 their degree of dependence. More details can be found in (Salvadori and De Michele, 2004; Nelsen, 2006). A

244 copula-based approach may be used to study the dependence of instantaneous SSs (or sea levels). In the case of a

245 copula of sea levels, no convolution is needed. The convolution of a copula of SSs with a density of tide permits to

246 obtain a copula of sea levels. This first solution is proposed herein as an alternative to the first procedure fitting

247 using the SSSs.

248 Second, we believe that a bias is introduced with the MSS based procedure because it does not take into account

249 the time difference between the maximum instantaneous SS and the high tide. A probability of coincidence (i.e.

250 the chance that a MSS occurs at the same time with high tide) can be used to better characterize the extreme sea

251 levels using the MSS. An appropriate coincidence probability concept would then allow to better estimate the

252 probabilities and thus reduce the bias and bring the RLs closer to those obtained by the reference method.

253 As shown in the right panel of figure 2 the MSS can occur randomly somewhere around the high tide M_n. The

254 time difference between the MSS and the high tide is random as well. One can introduce an additional random

255 variable to describe this temporal difference $\square$. Then a coincidence probability concept can be drawn as follows:

256 • Extract an independent sample of Δs

257 • Fit this sample with the POT method

258 • Choose a RL of □ (100-year RL, for instance) and use its probability to weight the probabilities of the

259 MSSs (i.e. assuming that MSSs and Δs are independent).

260 It is noteworthy that □ is a random variable and therefore it is quite legitimate to study it with a frequency analysis

261 method as the MSS.

262 Furthermore, figure 4 shows that extreme sea level events (the right tail of the distribution: the middle curve) tend

263 to occur at the time of the high tide, as expected. The results of this procedure confirm the general finding

264 highlighted in the literature (Duluc et al., 2012) that the return level estimations obtained with the convolution

265 tide-SSS are not adapted up to a certain return period (100 years in the case of Le Havre). To overcome this

266 problem, one can use an empirical method to define the left tail of the distribution and an extreme values analysis

267 for the right tail as stated by Tawn and Vassie (1989).

268 **6. Conclusions**

269 In the present paper, we provided detailed reasoning for the need, in a PFHA framework, to combine flood

270 phenomena to avoid over or under estimations of extreme water levels. Few ideas have been proposed in the

271 literature to tackle the combination of tidal signals with extreme SSSs to estimate extreme sea levels. The present

272 work supports these ideas, takes up the tidal signals and SSSs convolution procedure and proposes a new

273 procedure based on the MSSs useful to exploit likewise the extreme SS events occurred during medium and low

274 tide hours. Three fitting procedures have been investigated. The first one employs the SSS as an explanatory

275 variable with the tidal signals which are combined with a JPM using a convolution of the tide density and the SSS

276 distribution function. The second procedure uses the same technique except that the MSSs are used instead of the

277 SSSs. In the third approach, a frequency analysis is performed using ESLs.

278 Another consideration in this paper was applying and illustrating these approaches on the example of the sea levels

279 in Le Havre, northwestern France, over the period 1971–2015. It may be noted that the methodology is not

280 exemplary developed for this case study; it applies to any site likely to experience a marine flooding.

281 Fitting results in term of probability plots and extrapolated RLs using the three approaches are examined. Overall,

282 the application has shown that the RL estimates for MSS based convolution are quite different from those

283 corresponding to the SSS based one. It has also been suggested that the questions of coincidence and dependency

284 are essential for a combined tide and SS hazard analysis. Indeed, as shown in figure 4, the results of the second

285 fitting procedure are likely to contain a bias (comparing to the direct statistics on ESLs) which becomes more and

286 more important as return periods increase. In order to reduce this bias, the coincidence probability concept (i.e.

287 defined in this paper as the chance that a maximum SS occurs at the same time with high tide) can be helpful in

288 making a more appropriate assessment of the risk (associated to ESLs) using the MSS. On the other hand and if

289 the second procedure is to be used, the application has shown the utility of modelling the dependence structure that

290 exists between the hourly SS values around the high tide (high tide 3 hours). Figure 4 shows that ESL events (the

291 upper tail of the distribution: the middle curve) tend to occur at the time of the high tide, as expected. The results

292 of this procedure confirm the general finding highlighted in the literature is that the RL estimations obtained with

293 the convolution tide-SSS are not conclusive up to a certain return period (100 years in the case of Le Havre).

294 Perspective: An in-depth study could help to thoroughly improve the proposed procedure based on the use of MSS
295 by developing the concept of coincidence and apply the developed concept on other sites of interest. A concept of
296 coincidence and methodology to be developed should find additional applications for the assessment of risk
297 associated to other combining flooding phenomena (e.g. pluvial flooding and storm surges).

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381

382   **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'

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385 **Table 2: Sea RLs and 95% confidence intervals for the three fitting procedures (in meters)**
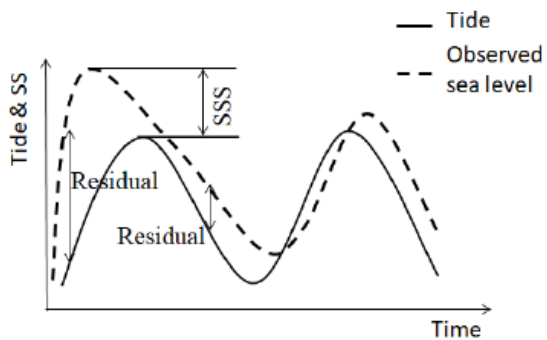
Method	T=10	T=50	T=100	T=1000
JPM-SSS	8.31 (8.27-8.35)	8.77 (8.72-8.82)	8.89 (8.84-8.95)	9.20 (9.07-9.32)
JPM-MSS	8.84 (8.79-8.89)	9.29 (9.22-9.36)	9.42 (9.33-9.51)	9.79 (9.58-10.01)
Frequency Analysis - ESL	8.82 (8.74-8.91)	8.99 (8.80-9.18)	9.05 (8.79-9.31)	9.22 (8.67-9.77)

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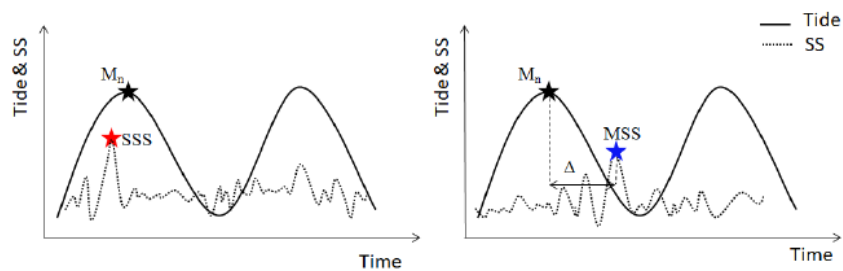and Earth System
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391 **Figure 1: Definition and schematic representation of a skew storm surge**
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395 **Figure 2: Illustration of tide and storm surge signals for the of joint surge-tide probability procedures: (left) skew**
396 **surge-tide combination; (right) maximum surge - tide combination**
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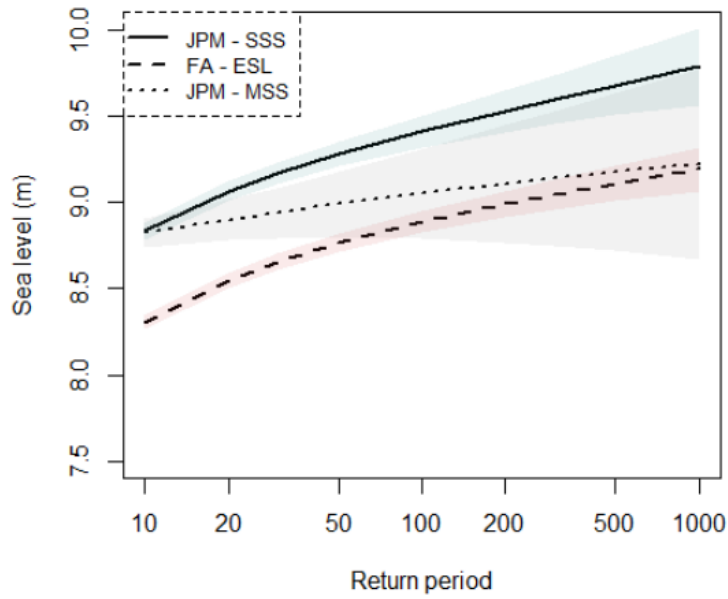400 **Figure 3: Case study (Le Havre): location map**

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403   **Figure 4: Sea level quantiles and confidence intervals**
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