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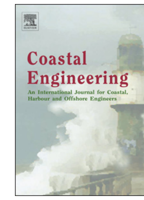

Estimating extreme water level probabilities: A comparison of the direct methods and recommendations for best practise

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A B S T R A C T

Over the past five decades, several approaches for estimating probabilities of extreme still water levels have been developed. Currently, different methods are applied not only on transnational, but also on national scales, resulting in a heterogeneous level of protection. Applying different statistical methods can yield significantly different estimates of return water levels, but even the use of the same technique can produce large discrepancies, because there is subjective parameter choice at several steps in the model setup. In this paper, we compare probabilities of extreme still water levels estimated using the main direct methods (i.e. the block maxima method and the peaks over threshold method) considering a wide range of strategies to create extreme value dataset and a range of different model setups. We primarily use tide gauge records from the German Bight but also consider data from sites around the UK and Australia for comparison. The focus is on testing the influence of the following three main factors, which can affect the estimates of extreme value statistics: (1) detrending the original data sets; (2) building samples of extreme values from the original data sets; and (3) the record lengths of the original data sets. We find that using different detrending techniques biases the results from extreme value statistics. Hence, we recommend using a 1-year moving average of high waters (or hourly records if these are available) to correct the original data sets for seasonal and long-term sea level changes. Our results highlight that the peaks over threshold method yields more reliable and more stable (i.e. using short records leads to the same results as when using long records) estimates of probabilities of extreme still water levels than the block maxima method. In analysing a variety of threshold selection methods we find that using the 99.7th percentile water level leads to the most stable return water level estimates along the German Bight. This is also valid for the international stations considered. Finally, to provide guidance for coastal engineers and operators, we recommend the peaks over threshold method and define an objective approach for setting up the model. If this is applied routinely around a country, it will help overcome the problem of heterogeneous levels of protection resulting from different methods and varying model setups.

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1. Introduction

Rising mean sea levels along with possible changes in storminess will increase the likelihood of coastal flooding around the world (Seneviratne et al., 2012), adversely impacting rapidly growing coastal communities. In 2005, 136 port cities had populations exceeding one million and thirteen of the twenty mega cities (populations >8 million) in the world were port cities (Nicholls et al., 2008). Globally, it is estimated that more than 200 million people are already vulnerable to coastal flooding in these cities and other coastal settlements (Nicholls, 2011). The Intergovernmental Panel of Climate Change's (IPCC) Fourth Assessment Report (Nicholls et al., 2007) suggested three options to cope with the increasing risk of coastal flooding, namely to *protect*, to *accommodate* and to *retreat*. In terms of protection there are two options, *advancing the line* and *holding the line*. Both of these options require flood defences which need to be precisely designed to offer both an appropriate level of protection over the life time of the structure but also to avoid over design.

For the efficient planning and design of coastal defence structures, it is important to understand the stochastic behaviour of extreme water level events (Jensen, 1985). Design levels for coastal defences are usually defined using some form of statistical analysis (Dixon and Tawn, 1994). These analyses are mostly based on extreme value theory, a special discipline in probability theory that deals with rare events, such as coastal floods (Coles, 2001). Over the last five decades, several different extreme value analysis methods for estimating probabilities

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of extreme still water levels have been developed (see Haigh et al., 2010a for an overview). There is, however, currently no universally accepted method available. Instead, different methods have been applied not only on transnational, but also on national scales, resulting in a heterogeneous level of protection. Applying different statistical methods can yield significantly different estimates of return water levels, and even the use of the same method can produce large discrepancies, because there is subjective choice at several steps in the model setup. In this paper, we compare estimates of extreme water level probabilities using two of the main extreme value analysis methods and conduct a systematic sensitivity assessment of the different steps involved in setting up and using these statistical techniques.

In Germany coastal protection is organised by government departments in federal states, who define design water levels using different methods. As a result, it is difficult to assess the level of protection offered by defences across the different federal states and equally difficult to compare this with neighbouring defences in the Netherlands and Denmark, who also use different statistical techniques. The German coastline has a total length of around 1,500 km with the two federal states Lower Saxony and Schleswig-Holstein directly bordering the North Sea. Two additional states, Hamburg and Bremen, are situated along tidal rivers (Elbe and Weser) that are strongly influenced by North Sea extreme water level events (Fig. 1). All states have developed their own methods (although with some level of coordination) to derive design water levels (only Lower Saxony and Bremen use the same approach). In Lower Saxony and Bremen, a deterministic approach is used to calculate design water levels, i.e. the mean tidal high water level is superimposed with the largest observed storm surge, the difference between the largest spring tide and mean tidal high water, and a projected mean sea-level rise (NLWKN, 2007). By contrast, design water levels in Hamburg are based on an empirically derived design flood for Cuxhaven which is transferred from Cuxhaven to Hamburg using a two-dimensional hydrodynamic numerical model of the Elbe River (Gönnert et al., 2013). Extreme value analyses are not part of the design procedure, but are applied afterwards in order to calculate the return period of the derived design water level. In the federal state of Schleswig-Holstein, the latest policy is to statistically derive design water levels associated with a 200-year return period using an extreme value analysis of the largest value per year superimposed with a projected mean sea-level rise (LKN, 2012). However, the choice of the model setup remains undefined. Hence, there is a considerable risk of subjectively influencing the return water level estimates.

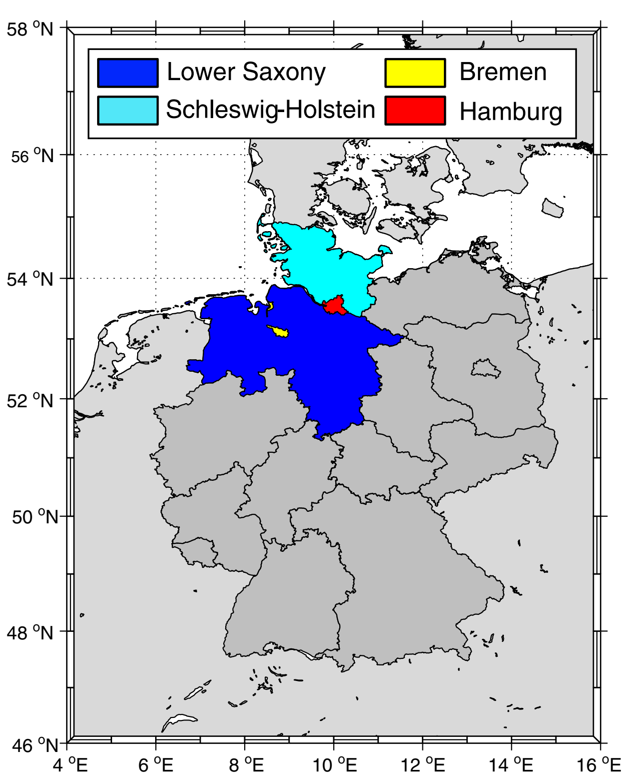

Fig. 1. The 16 federal states of Germany (depicted in dark grey). The four federal states being exposed to North Sea tides are shown in different colours according to the legend. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In England, estimates of extreme water level probabilities used to be determined for different stretches of the coastline by the different Environment Agency (EA) regional departments responsible for that area. However, on behalf of the EA, Dixon and Tawn (1994, 1995, 1997) provided a single coherent estimate of extreme still water level probabilities at high resolution all around the UK coastline using their Spatially Revised Joint Probability Method which was based on both tide gauge data and a multi-decadal predicted water level hindcast. A major update of that study has recently been completed (Batstone et al., in press; Environment Agency, 2011), which improved the basic statistical assumptions (resulting in the Skew Surge Joint Probability Method) and used longer tide gauge records that are now available. A similar study has recently been completed for Australia that provided a consistent estimate of the probabilities of extreme water levels at high resolution all around the Australian coastline (see Haigh et al., in press-a, in press-b) and is freely available for coastal engineers, managers and planners via a web-based tool (www.sealevelrise.info). Although, estimates of extreme water level probabilities are starting to be calculated systematically at high resolution all around the coastline of countries (e.g. the UK and Australia), there is still no universally accepted method that does not involve several subjective steps.

In this paper we compare probabilities of extreme still water levels estimated using the two main direct methods (i.e. the block maxima method and the peaks over threshold method) considering a wide range of strategies to create extreme datasets and using a wide range of parameters in the model set up. The sensitivity of both direct methods to three important factors is tested, each of which can significantly influence the results of the statistical analyses. These three factors are: (1) the detrending of the datasets; (2) the sample that is created according to the chosen model; and (3) the sensitivity of both distributions when steadily reducing the dataset lengths. The final point is undertaken to examine the consistency of the considered direct methods for datasets covering different record lengths.

Overall, the study has three main objectives:

(1) To briefly review the various steps involved in applying each method and describe the advantages and disadvantages of particular techniques involved;
(2) To test the sensitivity of the result from the extreme value analysis to the three factors mentioned above (i.e. detrending, sampling, and choice of distribution) and to develop an objective approach resulting in robust and stable return water level estimates that are applicable for design purposes; and
(3) To test the transferability of the defined approach, by applying this methodology to datasets from sites distributed along the northern European and Australian coastlines.

The overall aim of this paper is to provide guidance for coastal engineers, managers and planners who use these methods or the results produced by them. The challenge is in objectively obtaining stable results from extreme value analyses that are based on an automatically selected model setup and are spatially consistent on a national or even a transnational scale.

The structure of the paper is as follows: Section 2 summarizes the various approaches and required operations for extreme value analyses described in the literature. In Section 3, the considered sea level datasets are introduced. Results from analysing the performance of different model set-ups, primarily based on the Cuxhaven record, are shown in

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