USACE Extreme Sea levels

Progress Report 2~ Approved for Public release; Distribution unlimited.

9th September 2014

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Introduction

HR Wallingford and Southampton University are supporting the USACE in the development of an Engineering Technical Letter (ETL), in relation to extreme sea levels and climate impact adaptation. Lead personnel responsible for the USACE are Dr Kathleen White and Heidi Moritz. The work to be undertaken during this research effort includes:

1) Undertaking research to identify the underlying fundamental nature and influences of changes in extreme sea levels as they affect the four mission areas of USACE: storm damage reduction, flood risk mitigation, ecosystems management and navigation.

2) Involvement as appropriate in regular telephone conference calls with the ETL project team.

3) Production of one or more conference and/or peer-reviewed journal papers to disseminate the work.

4) Attendance at two ETL project meetings

5) Preparation and submission to IWR of a final report summarising the results of the research, together with a set of recommendations arising from the research.

This report describes progress to date (September 2014) on the project.

Progress

Progress to date comprises 5 main activities described below:

1. Attendance at bi-weekly phone calls starting in April – Haigh (2), Gouldby (9). Contributions include discussions related to all aspects of international approaches, sources of data and information and methods.
2. Final draft of text on international approaches for Chapter 4 (Appendix 1)
3. Telephone discussions with international colleagues on hierarchical approach of extreme sea level analysis and technical comments on hierarchy and summary of international applications that relate to the hierarchy.
4. Technical comments provided on Chapter 7 draft (Gouldby)
5. Comments and contribution to text on Chapter 5 (Haigh)

In the coming period it is anticipated that HR Wallingford and Southampton University will continue to support the team with the provision of text and technical comments across a number of chapters, in order to produce a first draft by the end of September.

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Appendix 1

Inputs from Peirson, Haigh, Wahl, Diemanse, Gouldby

Draft – 9th September 2014

Introduction

For the production of this ETL the USACE has undertaken an extensive international review of approaches that are adopted for undertaking extreme sea level estimates for use in the design of coastal structures and flood risk assessment. This review has identified a wide range of methods that have been adopted over many years. This section describes the findings of this review. The review is focused on four countries: UK, Australia, Germany and the Netherlands. Historical and present day approaches are described for each country. A summary is then provided which also identifies additional sources of information.

UK

The UK has a long history of severe coastal flooding. With the most notable events occurring in 1607, 1703 and 1953. The recent winter of 2013/2014 further emphasized the threat of coastal flooding with widespread coastal flooding experienced over a period of more than two months. Sea levels have been monitored at some locations for well over half a century. The national tide gauge network is now run within the National Oceanographic Centre (http://noc.ac.uk/ocean-watch/shallow-coastal-seas/uk-national-tide-gauge-network)

In the 60 years since the 1953 event, there have been many assessments that have estimated extreme sea-level probabilities for the UK, using a range of extreme value theories and these are summaraized by Haigh et al (2010). The first studies were undertaken by Lennon (1963) and Suthons (1963), and then Graff (1978). They used the annual maximum method to estimate return sea levels at tide gauge sites, but they were limited range of statistical models and inference techniques that were then available. Following that Pugh and Vassie (1979, 1980) developed the joint probability method (JPM) and applied this to records at UK tide gauge sites. This approach involved separate analysis of the astronomical tide and non-tidal residual (or surge). This was justified on the grounds that, in theory, surge is a true random variable and therefore more appropriate to use when applying extreme value methods for extrapolation.

Tawn and Vassie, (1989) and Tawn (1992) made two principle improvements to the JPM, which made it more widely applicable, and in the process developed the revised joint probability method (RJPM). These developments were exploited by Dixon and Tawn (1994, 1995, 1997) who provided the first coherent estimate of extreme still sea-level probabilities at high resolution all around the UK coastline using their so called 'Spatially Revised Joint Probability Method' (SRJPM). The SRJPM extended the RJPM by exploiting knowledge of the spatial variation of the tidal and surge components of the sea level around the UK and incorporating all the types of data available (annual maxima, hourly values and data from the CSX numerical storm surge model). A key output of the study was a set of tables containing return level estimates, relative to the 1 in 1 year return level, for a regular grid around the UK. Estimates of extreme sea level could be made at any location around the UK by simply combining these relative levels with an estimate of 1 year return level.

Around large parts of the UK there are considerable non-linear interactions between the tidal and meteorological induced components of sea level (Horsburgh and Wilson, 2007). The RJPM and SRJPM accounted for this by modelling the surge distribution conditional on the state of the tide. However, this relationship is complex for all shallow water sites and was a considerable source of complexity and uncertainty in these methods. A more recent study that has provided the latest set of extreme sea levels around the coastline of the UK, Environment Agency (2010), removes some of this complexity through use of the so-called ‘skew surge’ parameter, which is the absolute difference between the maximum recorded sea level during a tidal cycle and the predicted maximum astronomical tide. The skew surge simplifies the extreme value analysis and is considered a more robust indicator of the meteorological components of sea level around the relatively shallow waters of the UK. It is of note however, that this is not necessarily the case for different geographical locations with different tidal regimes.

This most recent study has seen the introduction of the Generalised Pareto Distribution (GPD) distribution for the first time. The GPD is fitted to peaks over threshold (POT) of the skew surge data. The reasons for using the GPD are discussed further below.

Australia

Australia is the largest nation that is completely surrounded by water, with an estimated total coastline (mainland plus islands) approaching 60,000 km. Approximately 85 per cent of the Australian population now live in the coastal region and it is of immense economic, social and environmental importance to the nation. All Australian state capital cities are located within the coastal zone.

In spite of its large coastline, Australia is relatively sparsely populated and, in international terms, has a short history of port development. Consequently, long term records of extreme coastal water levels are few. Early recognition of the significance of rising sea levels by the National Committee of Coastal and Ocean Engineering, Engineers Australia (NCCOE, 1991) established widespread recognition of the significance of coastal extreme water levels (EWLs)in the future development of Australia. A useful contemporary summary of EWL investigations undertaken in Australia is presented in Mariani et al. (2012), Table 3.3.

At the open coast, the astronomic tide, response to surface atmospheric pressure, wind set up, wave set up, wave run up and lower-frequency wave motions are all recognised as potentially significant contributors to extreme water levels at the coast. (NSW Government, 1990; NCCOE, 1991; NCCOE, 2012, Table 6; Carley et al., 2008, p.27)

Depending on the coast (and specifically, latitude), the significance of local extreme storms in determining design EWLs changes. As astronomic tide, tsunami and some other lower-frequency wave motions are not associated with storm passage, they may be assessed independently of those contributions which are directly storm related.

In more temperate regions, the coastal topography is generally steeper and the design storms of large horizontal scale. Consequently, inverse barometric behaviour can usually be assumed and, on the scale of most inundation studies, any systematic variation in surface pressure or wind can be neglected (e.g. Carley et al., 2008). As the landward distance inundated is usually limited due to the relatively steep coastal topography, the inundation region is usually determined by extrapolating the total EWL in a landward direction.

Elevated water levels due to tide, pressure and wind effects (say) can enable shoaling waves to break much further inland with significant consequent effects on local EWLs. In the tropics, where the topography is often much less steep and significant shifts in winds and surface pressure can occur on the scale of the inundation area under investigation, cyclonic climatologies and more sophisticated inundation modelling may be required (Harper et al., 2009).

Recent perceived priority for rapid assessment of coastal inundation due to sea level rise in Australia has spawned naïve approaches to EWL analysis that have encompassed the entire coastline (e.g. DCC, 2009). This has recently been extended during a major investigation using climatologies and global circulation reanalyses to yield predictions that are more consistent with Australian coastal engineering practice (Haigh *et al.*, 2014a, 2014b).

Application of EWL determination in Australia for engineering design is undertaken consistent with well-established approaches (e.g. the Coastal Engineering Manual).

Methodologies used in Australia as well as a national assessment of coastal setbacks are summarised and presented in Mariani et al. (2012). Community expectations of local government are presently high with local government now being expected to make decisions at a property scale (Booth and Cox, 2012). Consequently, some local and state government regulators are now requiring development proponents in contentious or potentially risky environments to prepare and submit detailed investigative studies for assessment if conservative approaches are deemed unacceptable (DECCW, 2009, p. 8).

Event risk management in Australia (particularly in terms of coastal inundation) is undertaken as a planned partnership between communities, State Emergency Services (informing and dealing directly with the community), and Federal and State agencies (particularly the Bureau of Meteorology) providing forecast data (e.g. DIPNR, 2005, Appendix N).

In more developed areas of Australia, the biggest potential impact of extreme coastal water levels is within estuaries. This is because the lengths of developed foreshore are much greater than that of the open coast.

Conventional approaches in Australia have tended to be conservative (DECCW, 2010b, p. 8). In the context of sea level rise, there is a present need to determine the level of adaptive capacity within existing estuary foreshore developments. A recent review of the influence of coastal EWLs on estuarine flooding by Smith et al. (2013) recommended an “envelope” approach to determining EWLs based on estuary type (their p. 66). Japanese investigators (e.g. Tanaka and Nguyen, 2008) found a significant influence of wave setup on estuary EWLs. This is in stark contrast with Australian field studies (e.g. Hanslow and Nielsen, 2011) and is presently being critically reviewed.

Germany

Germany has a particularly long history of severe coastal flooding. Perhaps the most devastating event in the last century occurred in February 1962 (The Hamburg Flood) when 315 people lost their lives (Butow 1963; von Storch and Woth 2006). This event, that followed the major 1953 event that affected the East Coast of the UK and the Netherlands led to substantial investment and upgrading of coastal defences.

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 and Hamburg and Bremen being situated along tidal rivers (Elbe and Weser) strongly influenced by North Sea extreme sea level events. Coastal protection in Germany is organized by government departments in these federal states and design water levels are defined using different approaches: Lower Saxony and Bremen use a deterministic approach, i.e. the highest observed surge is added (linearly) to the highest astronomical tide (NLWKN, 2007). Design water levels in Hamburg are based on a design surge derived from the observations at the tide gauge Cuxhaven, combined with a spring tide (tide-surge interaction is considered) and external surge (triggered in the north Atlantic and entering the North Sea); the total water levels are then transferred from Cuxhaven to Hamburg in the Elbe Estuary with a hydrodynamic model (Gönnert et al., 2013). In Schleswig-Holstein design water levels have a return period of 200-years and are derived from the highest water levels observed in a year (AMAX) with extreme value analysis (LKN, 2012). All three states account for potential future sea level rise of 50cm (linearly added to the design water levels). Due to the inconsistency in the applied methods, it is difficult to assess the level of protection offered by defences across the different federal states

To overcome the inconsistencies, Arns et al. (2013, 2014) estimated extreme sea-level probabilities along the entire northern coastline of Germany. Their methodology focused on testing the influence of the following three main factors, which can affect the estimates of extreme value statistics:

(1) De-trending the original data sets (i.e. accounting for long-term sea level rise and seasonal fluctuations);
(2) building samples of extreme values from the original data sets (i.e. using block maxima with annual maximum (AMAX) or the r-largest values per year, or peaks over threshold);
(3) the record lengths of the original data sets (i.e. how long must a record be. They focused on direct methods where the observed total water levels are directly analyzed instead of separating the tide and the surge (as it has been done in the UK for example).

This latter approach was preferred since tide gauge records with a temporal resolution high enough to apply tidal analysis techniques are relatively short. For most tide gauges only 15 to 20 years or less of (digital) high frequency data is available, but tidal high and low waters go back to the 1930s at many sites, and the mid to late 19th century at selected sites. The final outcome of the study by Arns et al. (2013) was the recommendation of an objective approach, with as little subjectivity as possible, which could be applied routinely around the coastline of Germany, to help overcome the problem of heterogeneous levels of protection resulting from different methods and varying model setups. They found that a time series length of ~40 years (including information from the extreme 1976 event) was sufficient to calculate accurate return water levels. Hence, in a subsequent step they conducted a 40-year water level hindcast with a hydrodynamic numerical model to obtain the required information for each coastal grid point (~ every kilometer; the focus was on the coastline of Schleswig-Holstein) (Arns et al., 2014). Using the setup of the extreme value model previously identified to be suitable for the area, they calculated return water levels for the entire coastline of Schleswig-Holstein, including the offshore islands from which no or only very sparse observational data is available . Further work is planned to extend the study to include the coastline of Lower Saxony.

In a research project XtremRisK (https://www.tu-braunschweig.de/lwi/hyku/xtremrisk/) integrated risk analyses were conducted for the city of Hamburg (or parts of it) and the biggest German North

Sea Island Sylt (in particular the cities of Westerland and Hörnum). In this project multivariate statistical models were used to calculate the (joint) probabilities of the occurrence of a range of storm surge (and wave) events (Wahl et al., 2011, 2012), failure probabilities were determined, inundation models were applied, and damages in the hinterland were assessed (see Oumeraci et al., 2012 and references therein for an overview). Such risk-based approaches will likely become more important in the future but are not yet feasible to be applied widely to entire coastline stretches.

The Netherlands

Approximately 25% of The Netherlands is below sea level and about 60% is flood prone. Since the Dark Ages, flood defences have been constructed to protect the flood prone areas. Major flood events often lead to new approaches towards flood defence management.

The most recent flood disaster in The Netherlands was the February 1953 event which caused over 1800 casualties in the south-western part of the Netherlands. In the follow-up of the event, a national committee was established, the Delta Committee, to advise the government with respect to mitigating measures and the approach for design and assessment of flood defences. The Delta Committee proposed to shorten the coastline by building storm surge barriers (the Delta Works) and to further decrease flood risks through establishment of stringent standards for protection by flood defences (Delta Committee 1958).

For the design and safety assessment of the flood defences, protection standards have been defined in terms of "allowable flood frequencies". The present protection standards vary from 10-3 to 10-4 per year. The foundation of the flood protection standards was laid by Van Dantzig (1956) and formally established in Delta Committee (1958). The protection standards are currently being reconsidered, following the advice of a newly established Delta Committee (Delta Committee, 2008). The new standards for safety assessments will be based on an advanced cost-benefit analysis (Kind, 2013) and on flood fatality risk assessments (De Bruijn et al, 2010).

The next round of safety assessments of the primary flood defences will commence in 2017. A new probabilistic safety assessment model, Hydra-Ring, is currently being developed for this purpose (Den Heijer and Diermanse, 2012). The model combines statistical information on hydraulic loads in the primary water systems with failure mechanisms models and field data on flood defences in order to estimate failure probabilities of the entire flood defence system.

The hydraulic load models for the coastal areas in Hydra-Ring use separate (but correlated) statistics for still water levels (SWL) and waves. The probability distributions of the SWL are based on a comprehensive study carried out in several stages from 1985 until 1995 (Dillingh et al., 1993, Philippart et al., 1995). Extreme value theory was used to extrapolate observed surge peaks at five stations in the North Sea. Several statistical distributions, including the generalized Pareto distribution (GPD), as well as distribution-free methods were tested, and a distribution-free method referred to as the "VVM-0 method" based on de Haan (1990) and de Haan and Rootzén (1993) was selected to statistically estimate the 1/10,000-year surge at the five stations.

Subsequently, physically-based numerical models were applied to estimate the 1/10,000-year SWL at the five stations, since 1/10,000 is the protection standard for most coastal flood defences in The Netherlands. The final estimate for the 1/10,000-year SWL was taken to be a weighted average of the statistical and physical estimates (Philippart et al., 1993). The estimates of the 1/10,000-year SWL were then spatially interpolated so that extreme SWL estimates would be available at other locations besides the five base stations (Philippart et al., 1995). The 1/10,000-year SWL levels, based on combined statistical and physically-based estimates at the base stations, and on spatial interpolation thereof at other locations, were no longer part of a statistical distribution. To address this, the generalized Pareto distribution (GPD) was fitted through three points: 1) the 5/10-year SWL, 2) the 1/10-year surge, and 3) the 1/10,000-year SWL estimate (Philippart et al., 1995). The first two points can be derived directly from the measurements, and the third point is the value that represents the weighted average of statistical and physical estimates (or the interpolation thereof for stations other than the five base stations).

Since 1995 no major efforts have been carried out to update the extreme SWL statistics for the formal safety assessment procedures. Approximately every 6 years the statistics are, however, corrected for influences of sea level rise. Furthermore, the additional six years of measurements are used to evaluate whether a major update of the SWL statistics are required. So far, updates were not considered necessary as no major storm events were added to the series. A new re-evaluation is planned in 2014.

The extreme SWL statistics as described above related to peak water levels. For some failure mechanisms, event durations are also relevant. Furthermore, in the hydrodynamic models that are used in the of the load models in Hydra-Ring, wind fields are generally assumed to be spatially uniform, which is a simplification. For these reasons, a research project was initiated with the objective to produce realistic time- and space-varying synthetic wind fields and water levels (Groeneweg et al, 2012). The results of the research are anticipated to be integrated in the safety assessment model (Hydra-Ring) five to ten years from now.

Summary

Text to follow

Further information on extreme sea levels for each of the countries is provided in Table 1

Table 1:

Country	**Papers**	**Reports**	**Websites**
UK	Lennon (1963) Suthons (1963) Graff (1978) Pugh and Vassie (1979, 1980) Walden et al. (1982) Tawn, (1988b) Tawn and Vassie, (1989) Tawn (1992) Coles and Tawn (1990, 1991) Dixon and Tawn (1994, 1995, 1997) Flather et al., 1998 Coles and Tawn, 2005 Horsburgh and Wilson (2007).	Environment Agency (2010) McMillan, A., Batstone, C., Worth, D., Tawn, J. A., Horsburgh, K. & Lawless, M. 2011. Coastal flood boundary conditions for UK mainland and islands. Project: SC060064/TR2: Design sea levels.: Published by: Environment Agency, Bristol, UK. Swift, R., 2003. Extreme water levels — an interregional comparison. ABPmer Internal Report Number R1058.	National tidal measurement network: http://noc.ac.uk/ocean-watch/shallow-coastal-seas/uk-national-tide-gauge-network British Oceanographic Data Centre: http://www.bodc. ac.uk
Germany	McInnes & Hubbert (2003) McInnes et al. (2009) Arns, A. et al. (2013) Arns, A. et al. (2014)		
Australia	McInnes & Hubbert (2003) McInnes et al. (2009) Harper et al. (2008) Harper et al. (2009) Haigh et al. (2014a, b)	Harper BA (ed) (2001) Queensland climate change and community vulnerability to tropical cyclones—ocean hazards assessment stage 1—review of technical requirements.	http://canute2.sealevelrise.info

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