Institution: Lancaster University

Unit of Assessment: UoA 10: Mathematical Sciences

Title of case study:
Optimisation of the UK's flood defence infrastructure through the use of innovative statistical research on extreme values

1. Summary of the impact (indicative maximum 100 words)

The UK spends £400-500M per year on flood defence infrastructure with 2 million properties exposed to the risk of flooding. Lancaster's research on extreme value methods is fundamental to optimising the design of this infrastructure to protect against coastal and river extreme events. This optimisation minimises costs without jeopardising the level of accepted risk and hence has financial and societal benefits. These methods are the fundamental component in:

- The design of all UK's coastal flood defences, total spend of £900M on 900 schemes over the REF census period.
- Saving the UK government £6M over this period from consultant fees.
- International governments' and the insurance industry's assessment of widespread river flooding risk.

2. Underpinning research (indicative maximum 500 words)

Overview of Research

Estimating the frequency of events that are more extreme than any previous observation is a key element in environmental risk prevention and assessment. Extreme value theory, a core research area at Lancaster for 20 years, provides mathematically justified models as the basis for extrapolations from observed large events out to more extreme events. The underpinning research at Lancaster for flooding comprises univariate, multivariate and spatial extreme value analysis and consists of two papers in the prestigious RSS discussion paper series as well as a series of papers in the journal Applied Statistics. Bortot, Coles, Dixon, Heffernan, Keef and Tawn were all based at Lancaster when the cited research was undertaken. Our research provides novel statistical methodologies that integrate knowledge of the structure of oceanographic and hydrological processes with substantial developments in extreme value theory. Indirect evidence of the importance of this research to the UK government is shown by DEFRA and Environment Agency funding of £780K to support Lancaster's research on extreme value methods and their application to assessing the risk of flooding.

Coastal Flooding

For coastal flood defences the two key design parameters, in order of importance, are still water level (sea level with waves averaged out) and overtopping rate (a combination of wave characteristics and still water level).

Still water level is the sum of two components: tide (deterministic) and surge (stochastic). Dixon and Tawn developed the first extreme value methods which accounted for any of the following features: the tide-surge decomposition; interaction between the tide and surge; the spatial coherence of the surge; the use of hydro-dynamical models that predict the tides at intermediate sites; and inference using all extreme events (see e.g. Dixon et al. 1998). These developments required novel theory for temporal extremes and sophisticated covariate and spatial smoothing for extremes. The outcome was the first set of systematic estimates of extreme still water levels for the entire UK coastline that has no bias and much smaller confidence intervals than previous methods. Tawn provided the statistical expertise in a recent adaptation of these methods by Batstone et al. (2013) that updated estimates by using the additional recent data and instead of surge used a characteristic known as skew surge that removed the need to model the tide-surge interaction.

For extremes of overtopping rate the joint distribution of still water level, wave height, wave period and direction needs modelling in its extreme tails. This involves univariate modelling of the tails but also multivariate extreme value theory for the dependence structure. Coles and Tawn (1994) identified the benefit of treating these approaches as multivariate, developed a generic Poisson process approach and illustrated its use in the overtopping problem. The methods were later tuned for overtopping by Bortot et al. (2000) using simplified dependence models that gave sufficient flexibility but were robust.

River Flooding and Risk Assessment

Until Heffernan and Tawn (2004) multivariate extreme value methods were restricted to low dimensional cases with restricted forms of dependence structure, with the methods relying on an underlying assumption of multivariate regular variation. Heffernan and Tawn (2004) addressed the problem from an orthogonal approach by looking at limit theory conditionally on a component of the vector variable being extreme. This opened the methodology to substantive application for high dimensional analyses and a broad range of dependence structures. The work was extended and tailored for application to river flooding in Keef et al. (2009), addressing issues such as how to deal with missing data and temporal dependence.

3. References to the research (indicative maximum of six references)

Key references

Coles, S. G. and Tawn, J. A. (1994). Statistical methods for multivariate extremes: an application to structural design (with discussion), Appl. Statist., 43, 1-48.
Dixon, J. M., Tawn, J. A. and Vassie, J. M. (1998). Spatial modelling of extreme sea-levels, Environmetrics, 9, 283--301.
Heffernan, J. E. and Tawn, J. A. (2004). A conditional approach to modelling multivariate extreme values (with discussion), J. Roy. Statist. Soc., B, 66, 497--547.

Other references

Batstone, C., Lawless, M., Tawn, J. A., Horsburgh, K., Blackman, D. McMillan, A., Worth, D., Laeger, S., and Hunt, T. (2013). A UK best-practice approach for extreme sea level analysis along complex topographic coastlines. Ocean Engineering, 71, 28-39
Bortot, P, Coles, S. G. and Tawn, J. A. (2000). The multivariate Gaussian tail model: an application to oceanographic data, Appl. Statist., 49, 31-49.
Keef, C., Tawn, J. A. and Svensson, C. (2009). Spatial risk assessment for extreme river flows. Appl. Statist., 58, 601-618.

4. Details of the impact (indicative maximum 750 words)

Impact on Design of Coastal Flood Defences

The North Sea floods of 1953 claimed 307 lives in the UK and 1,800 in Netherlands. Following that event more rigorous methods of data collection and analysis were used in coastal flood defence design. Large budgets are involved, e.g., the total spend on defences on the UK east coast in Lincolnshire, Norfolk, Suffolk and Essex was £250M in 10 years. In designing a sea-wall the key design factor is its height which needs to be estimated to ensure an intended level of protection, which typically corresponds to events larger than those already observed. If the wall is built too high then substantial unnecessary costs can be incurred: 1m of extra height on average costs £150K per 100m length of wall with the UK having about 1000km of walls (JBA 2013). If it is too small then the intended level of protection will not be achieved, with flooding occurring at a greater frequency than anticipated and hence unacceptable risks to human life/property and effects on longer-term property value. Therefore major economic and societal benefits arise from optimising the wall height.

Design standards for a typical coastal town are based on 100-year return levels, which corresponds to the sea-wall height that would be exceeded on average once in 100 years. Prior to the underpinning research for this study, different methods had been used giving estimates for the

100-year level return level at a site that varied by between 0.5-1m for each of the 30 sites with data and by much greater larger amounts at intermediate sites without observations (Dixon and Tawn, 1997).

Using the new methods for inference for extreme still water levels developed at Lancaster, Dixon and Tawn (1997) produced the first set of estimates of still water extremes for the entire UK coastline. Following strong recommendations from DEFRA and the Proudman Oceanographic Laboratory (now the National Oceanography Centre) these values were **used in all designs of UK coastal flood defence designs from 1997 to 2010** (JBA, 2013). In 2008-10 Tawn provided the statistical expertise in a consortium with JBA Consulting, the National Oceanography Centre and Royal Haskoning to update the methods, exploit new data, and produce a new full set of estimates for the Environment Agency that have been used systematically by the Environment Agency and their clients since 2010 (Environment Agency, 2011, Batstone et al 2013). In particular, these estimates have been used to determine the **design of over 900 schemes, total spend £900M** (JBA 2013)**,** over the REF census period.

Even when the still water level does not breach the sea-wall, substantial flooding can occur due to overtopping by waves. Using the methods described in Section 2 for dependence modelling, joint work with HR Wallingford (Bortot and Tawn, 1998; Hawkes et al., 2002) led to the software JOINSEA. This software "*set the standard for joint probability analysis in the UK flood risk studies, and probably remains the industry standard for joint probability assessments in coastal assessments […] because it is practically the only method used*." (HRW 2013). It has been used throughout the REF census for determining the designs of all UK coastal flood defences to reduce the wave overtopping to an acceptable level. In 2010, Eastoe (at Lancaster) and Tawn with Royal Haskoning produced for the Environment Agency joint distributions of wave characteristics (wind-sea waves and swell waves) around the UK for more systematic use.

Both the still water and wave estimates we produced are specified by the Environment Agency (see e.g., Environment Agency, 2013; which refers to these as Coastal Flood Boundary Data) as the key input into cost-benefit analyses that have to be undertaken before any design for new flood defences is approved. For still water level the estimates differ from earlier values by 20-30 cm, which, if half are lower, corresponds to an estimate of a **saving of £22.5M** on 450 schemes of 100m long. Additionally the creation of these estimates saves the UK government paying consultant fees for deriving these estimates separately for each site (previously typically costing £15K per schemes, see JBA 2013) **leading to a saving since 2010 of over £6M** (based on 450 of the 900 schemes in the REF census being developed since 2010). Stefan Laeger (Research Scientist at the Environment Agency), writes:

"The outputs from EA R&D project SC060064 'Coastal Flood Boundary Conditions' produced a new, up-to-date national evidence base and dataset on design sea level conditions for mainland UK. This dataset is now the de facto industry standard in mainland UK and has been used to inform the vast majority of new coastal work (defences, strategies, risk maps etc) since summer 2011. Through Tawn's expert input, we were able to ensure that this dataset was produced by using improved, more scientifically robust statistical methods for analysing these extreme conditions."

Impact on Risk Assessment of River Flooding

The risk of river flooding is managed by society through a combination of governmental agencies and the insurance industry. For both these types of organisation an estimate of the likelihood of the large or widespread flooding events is essential. Such estimates are used by government to help in coordinating flood mitigation activities and by the insurance industry to assess the financial risk of claims associated with their insurance portfolio. These demands call for spatial extreme value methods, for which the only viable option is the novel method developed by Heffernan and Tawn (2004) at Lancaster and described in Section 2. The need for such tools is illustrated in the UK by large-scale floods in 2000-1 (£1B insurance loss), 2007 (£3B insurance loss with 55,000 properties flooded) and 2012 (£1B insurance loss).

The UKs two leading companies working on hydrological risk assessment, JBA Consulting and HR Wallingford (combined annual turnover in excess of £40M), have interfaced Lancaster's conditional spatial extremes statistical work developed for rivers with hydrological models and housing databases to produce tools to quantify the risks of spatial dependence in flooding for the first time (e.g., JBA's portfolio analysis tool 'JCALF' http://www.jbarisk.com/software, Keef et al., 2013).

This software enables users to estimate accurately the distribution of the annual total flood loss for their portfolio of insured properties. This distribution is vital to the insurance companies in determining which new properties to insure and for assessing how much reinsurance they require to satisfy regulators. Without having an accurate model for the joint distribution of different rivers flooding this loss distribution cannot be accurately estimated and hence conservatism is applied in estimates, resulting in substantial over-estimation of the amount of reinsurance required. The key to this software is therefore the high quality of the statistical model for multivariate extremes developed at Lancaster and applied to extreme river levels jointly by research at Lancaster and JBA Consulting,

An example of the use of this approach is that JBA Risk Management Ltd. have developed such risk assessment products which have been licensed to several major international clients operating in the catastrophe analysis and reinsurance sector in the UK, France, Poland and India (JBA 2013). Therefore there are substantial economic benefits from the research for the insurance industry and consequently society.

5. Sources to corroborate the impact (indicative maximum of 10 references)

Batstone, C., Lawless, M., Tawn, J. A., Horsburgh, K., Blackman, D. McMillan, A., Worth, D., Laeger, S., and Hunt, T. (2013). A UK best-practice approach for extreme sea level analysis along complex topographic coastlines. Ocean Engineering, 71, 28-39

Bortot, P. and Tawn, J. A. (1998). Joint probability methods for extreme still water levels and waves. HR Wallingford report, SR537, 234 pages.

Dixon, M. J. and Tawn, J. A. (1997). Spatial analyses for the UK, Proudman Oceanographic Laboratory report, 112, 200 pages.

Environment Agency (2011). Coastal flood boundary conditions for UK mainland and islands. Project: SC060064/TR2: Design sea-levels. Environment Agency of England and Wales.

Environment Agency (2013). Outline brief for Cornwall Coastal Flood Risk Modelling: Plymouth Sound and Tamar Estuary. Environment Agency.

Hawkes, P. J., Gouldby, B. P., Tawn, J. A. and Owen, M. W. (2002). The joint probability of waves and water levels in coastal defence design. J. Hydraulic Research, 40, 241--251.

Keef, C., Tawn, J. A. and Lamb, R. (2013). Estimating the probability of widespread flood events. Environmetrics, 24, 13-21.

Letter of Support from Principal Engineer, HR Wallingford Ltd (HRW 2013)

Letter of Support from Chief Scientist, JBA Consulting (JBA 2013).

Letter of Support from Research Scientist, Environment Agency.