Institution: Lancaster University		
Unit of Assessment: 10, Mathematical Sciences		
Title of case study: A step-change in the understanding and quantification of risk to improve resilience to flooding: supporting GBP2.6billion UK Government spend		
Period when the underpinning research was undertaken: 2000-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Jonathan Tawn	**Role(s) (e.g. job title):** Distinguished Professor of Statistics	**Period(s) employed by submitting HEI:** 01/09/1992 - present
Period when the claimed impact occurred: 2014-2020		
Is this case study continued from a case study submitted in 2014? N		

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

Lancaster research has played a crucial role in building resilience to extreme flood events, the second largest natural hazard in the UK Government's National Risk Register of Civil Emergencies is flooding (after pandemics). The research of Professor Tawn and his team on extreme value methods has produced a step-change in the quantification of spatial and multi-hazards for inland and coastal flood events, and is fundamental to:

Government planning:

- The ***first assessment of the probability of a flood occurring somewhere in the country*** in a year for the ***UK Government's 2016 National Flood Resilience Review***.
- Developing the widespread flooding scenarios for the ***UK's National Risk Assessment*** related to river, coastal and estuarine flooding, with the ***improved understanding being estimated to have led to GBP40million of savings*** over the 2016 and 2020 flood events.

Improved Risk Estimation:

- Maximising the efficiency of ***all new UK coastal flood defences***, with respect to both still water levels and their combined effect with waves***, leading to estimated savings of GBP75million on coastal defences and over GBP1billion for defences at nuclear sites***.
- Providing major international reinsurance companies (including UK and French state backed companies Flood Re and CCR respectively) with simulated extreme event sets to assess the probability of catastrophic flood losses, for business planning and regulatory requirements.
- Publicly available software used by over 100 companies for flood risk assessment.

2. Underpinning research (indicative maximum 500 words)

Overview of Research Area: Estimating the frequency of events that are more extreme than any previous observation is a key element in environmental risk assessment and prevention. Extreme value theory provides mathematically justified models as the basis for extrapolations from observed large events out to more extreme events. Extreme value theory and its methods and applications, particularly in relation to environmental problems, has been a core research area at Lancaster for over 25 years. Professor Tawn lead on the underpinning research, and Prof Phil Jonathan, Dr Emma Eastoe and Dr Jennifer Wadsworth are also key members of the Extreme Value Statistics group. Co-authors for the cited papers, below, were predominantly at Lancaster as PhDs or PDRAs when the work was undertaken. This work contributed to Professor Tawn being the inaugural winner of the RSS Barnett Award 2015 for outstanding contributions to environmental statistics.

The underpinning research falls into two district sub-areas of extreme value theory, each of which addresses challenges faced in the statistical analysis of environmental extremes. These are **Conditional Multivariate and Spatial Extremes** and **Extremes for sea-levels,** with the underpinning research including a landmark paper [3.1] in the prestigious RSS discussion paper series in JRSSB as well as papers in Spatial Statistics and Environmetrics.

Conditional Multivariate and Spatial Extremes: Multivariate extremes involve the joint analysis of multiple hazards, such as sea and river levels in an estuary. Such hazards can cause different levels of failure to infrastructure dependent on which extreme combinations of hazard level occur simultaneously, and thus having estimates of the probabilities of these different occurrences is vital. Here the development of flexible asymptotically justified dependence models and the associated inference methods for the tail region of the joint distribution are of fundamental importance. In many cases these same methods can also be applied for spatial modelling of a single hazard at multiple locations, for example river levels on a network of rivers or sea-levels along a coastline.

Prior to Lancaster's research, multivariate extreme value methods were restricted to low dimensional cases and relied on the very strong and restrictive underlying asymptotic assumption of multivariate regular variation. Though convenient mathematically, this assumption was rarely found to be consistent with properties of environmental data and, if used, would typically result in an overestimation of the risk, resulting in an over-conservative design. Research in 2004 by Heffernan and Tawn [3.1] addressed the problem through an entirely novel limit theory, conditioning on a component of the vector variable being extreme. This limit result and associated models have produced a step-change in the methodology for multivariate extremes enabling substantive application for high dimensional analyses and a broad range of dependence structures. It has been applied widely in environmental and financial contexts, with over 500 citations. The model in [3.1] has been extended and tailored for application to river flooding [3.2], solving problems of large (>1000) dimensionality, and simulation of extreme event sets. The first formulation of this model into a fully spatial context, particularly important for environmental applications, was developed [3.3]. Important risk measures were derived [3.4] and subsequently extended [3.5] to address multi-hazard problems in fully integrated risk assessments.

Extremes for sea-levels: For coastal flood defences the key design parameter is still water level, the sum of two components: tide (deterministic) and surge (stochastic). Standard extreme value methods cannot be applied directly to extreme still water levels due to the substantial variations due to the tide. Research at Lancaster in the 1990s gave the first systematic estimates of extreme still water levels for the entire UK coastline that had no bias and improved confidence interval accuracy over previous methods. In 2013 Tawn provided the statistical expertise in more advanced methods that enabled updated estimates using the extra data [3.6]. This was achieved by modelling a feature known as skew surge that, due to physical considerations, removes the need to model the tide-surge interaction giving a stronger justification for extrapolation.

Partnership with JBA: JBA, an employee-owned firm based in the UK and operational on five continents, is an engineering and environmental risk management business specialising in flooding. Since the late 1990s, JBA has been a framework consultant for the Environment Agency (EA), the official risk management authority in England. The firm also supplies flood data to the insurance industry in the UK and globally. The partnership includes JBA's Chief Scientist Professor Rob Lamb (20% FTE at Lancaster since 2015 as professor in practice and an honorary appointment from 2013), a number of JBA's staff participating in Lancaster's Extreme Value Statistics reading group, 3 funded and co-supervised PhD students, 3 ex-Lancaster PhD students appointed by JBA and a joint KTP project.

Key to this impact case study is that the Lancaster Extreme Value Statistics group works closely with JBA's hydrologists, oceanographers and environmental modellers to ensure that research developments address key industry problems, incorporate known science, and that their associated solutions can be implemented. The 12 year-long strategic research partnership between Lancaster University and JBA provides direct pathways into impacts through influence on Government policy and delivery of flood risk management actions, such as programmes funded by the EA and risk assessments for re/insurers.

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

[3.1] 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. https://doi.org/10.1111/j.1467-9868.2004.02050.x

[3.2] Keef, C., Tawn, J. A. and Lamb, R. (2013). Estimating the probability of widespread flood events. Environmetrics, 24, 13-21. https://doi.org/10.1002/env.2190

[3.3] Tawn, J. A., Shooter, R., Towe, R. and Lamb, R. (2018). Modelling spatial extreme events with environmental applications. Spatial Statistics, 28, 39-58. https://doi.org/10.1016/j.spasta.2018.04.007

[3.4] Lamb, R., Keef, C., Tawn, J. A., Laeger, S., Meadowcroft, I., Surendran, S., Dunning, P. and Batstone, C. (2010). A new method to assess the risk of local and widespread flooding on rivers and coasts. Journal of Flood Risk Management, 3, 323-336. https://doi.org/10.1111/j.1753-318X.2010.01081.x

[3.5] Towe, R., Tawn, J. A. and Lamb, R. (2018). Why extreme floods are more common than you might think? Significance, Vol. 15, No. 6, 16-21. https://doi.org/10.1111/j.1740-9713.2018.01209.x
[3.6] 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. https://doi.org/10.1016/j.oceaneng.2013.02.003

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

Overview

Historically, flood mitigation has been reactive, but each major flood event is different, as shown by [3.5], and this makes preparation and planning a challenge. Government needs to understand the likelihood of widespread flooding so that it can plan the emergency responses that protect people and infrastructure when floods occur. Public and private infrastructure owners need to know about the probability of extreme flood events so they can make optimal investment decisions to ensure their assets are resilient. Insurers and reinsurers need to assess the probability of large-scale catastrophic financial losses across their portfolios so they can determine premiums and comply with regulatory requirements under the Solvency II directive in the UK and Europe. Lancaster's research in extreme value methods has been instrumental in developments by JBA and HR Wallingford, the UK's two leading engineering and environmental risk management businesses specialising in flood management. Our close partnership with JBA provides a pathway into impact, with our underpinning research and collaborative work with JBA directly influencing HR Wallingford's methodology for coastal flooding. Evidence for this comes through detailed letters of support from JBA's Executive Chair, who states that "*Our work … has confirmed that the Heffernan and Tawn (2004) methodology is also the most suitable statistical approach to model the joint probability of inter-related flood hazards*" [5.1], and from HR Wallingford's Chief Technical Director, who reports that the "*Heffernan and Tawn (2004) paper …has produced a step change in our ability to quantify extremes relating to flooding and the design of flood defence infrastructure."* [5.2]

Through JBA and HR Wallingford, our research has influenced the UK Government to produce step changes in flood resilience through improved planning and flood risk estimation. Over the census period it has had ***substantial impact on GBP2.6billion spent*** on flood risk ***to*** better protect **300,000 homes** and to **reduce the annual flooding damages of around GBP 1.6 billion** [5.9]. In 2020 the UK Government committed to spend GBP5.2billion on flood risk over the period 2021-7. The ***industry standard for sea walls heights in all new UK coastal flood designs over the period 2014-20 use our statistical methods*** [5.3]; and estimated savings to the UK Government over the census period include ***GBP8million in consultancy fees*** [5.3]; ***GBP40million on the UK wide flood events since 2016*** [5.2], and ***over GBP1billion due to improved designs*** [5.2]. Our methods are now routinely used for all England's multivariate and spatial flood risk evaluations with work commissioned at JBA and HR Wallingford through the EA [5.1, 5.2 and 5.3]. They are also ***used worldwide for reinsurance*** [5.1], via JBA providing software products, with key users including UK and French state backed companies Flood Re and CCR respectively. They have also been of vital importance in forming the UK Government's strategy and understanding via ***the National Flood Resilience Review and The National Risk Assessment/Risk Register of Civil Emergencies*** [5.4 and 5.6]. Our impact is developed through four pathways below, which reflect the multiple needs of flood management set out above. All share a common requirement for multivariate statistical analysis of flooding that is theoretically rigorous, enabling extrapolation to events more extreme than previously experienced, and that can capture the complex nature of both localised and widespread flooding.

4.1 Government Planning:

Input into UK Government National Flood Resilience Review (NFRR) 2016

The NFRR was set up by HM Government in 2016 after "*extreme flood events across wide areas of the country … to assess how the country can be better protected from future flooding*" [5.4, Ministerial Foreword, p. 1]. It was chaired by the Chancellor of the Duchy of Lancaster (then the Rt Hon Oliver Letwin) and included representatives from The Prime Minister's Office, Cabinet Office and the Treasury. The Executive Summary [5.4, p.3, 4th para] said that the first task in the Review was to "*improve our understanding of … flood risk in England*", going on to state "*we have* *become clear that describing flood risk in traditional terms such as … '1 in a 100-year risk' is not helpful because … they describe the risk at one location. They do not describe the chance of one of these events happening somewhere in the … country in a given year – which is much greater".*

This improved understanding of risk was entirely informed by the statistical research of Tawn, [3.1] and his translatory work with Lamb at JBA [3.2-3.5]. The NFRR [5.4, p. 12] cited this analysis as "*a method developed at Lancaster University and JBA*" showing that "*while the probability of an extreme river flow that could result in a severe flood at any given location is very small, such flows are not unusual when considering the whole country*". The work produced for NFRR, reported in [3.5] and based on the fundamental results of [3.1], shows the estimated probability of getting a marginal 1 in 100-year flood at some flow gauge in England and Wales in a 1-year period is as high as 0.88, and it also gives a range of other regional flooding probabilities. This "*evidence and analysis which informs policy*" and that "*stands up to challenges of credibility, reliability and objectivity*", was scrutinised by a "*Scientific Advisory Group*" [5.4, p.11]. The Group was chaired by the Chief Scientific Adviser to the Government and Head of the Government Office for Science, Sir Mark Walport, and included the Chair of the Defra Science Advisory Council, the Environment Agency (EA) Chief Executive as well as Tawn and Lamb. Sir Mark Walport's personal letter to Tawn thanked him and stated that "*Communities at risk of flooding were looking for a decisive government response to the severe and high-profile flooding events, particularly of last December. There was pressure on Government to better understand the risks involved…* ***Your contribution to the review was very important.*** *Ministers were determined to base the review's conclusions and recommendations on sound evidence and analysis, and our assurance of the quality of science was seen as central. … Our advice had significant influence on both the evidence and the way in which it was communicated. Importantly, you were able to highlight key uncertainties and limitations.*" [5.5]

Input into UK Government National Risk Assessment (NRA) 2017

UK Government makes a biennial national assessment of possible civil emergencies (such as extreme weather, accidents or disease). This classified National Risk Assessment, and its public face the National Risk Register [5.6], hinges on scenarios that would stretch the emergency services' capacity to respond, and yet represent plausible, extreme events that could occur over the next five years within specified probability ranges. Statistical models [3.1, 3.2] ensured that the proposed scenarios were consistent with observed patterns of extreme events and based on a theoretically sound approach to extrapolate beyond the historical data. ***They enabled the probability of widespread flood and coastal extremes to be quantified rigorously, forming the basis for three national scenarios: flooding from rivers, flooding from surface drainage and flooding from the sea*** [5.1, 5.2]. The research by JBA and Tawn underpinning the NRA scenarios was published in an EA report [5.7], with the EA's web page stating it "*developed methods and guidance to address the need for realistic planning scenarios that account for the risk of widespread flooding across England and Wales, flooding from multiple sources (river, surface water) and the potential impacts."* HR Wallingford's associated research, reported in the appendix of [5.2], builds upon [3.1] and resulted in an improved spatial understanding of flooding which has led to GBP40million of savings over the UK wide 2016 and 2020 flood events [5.2]. This work was recognised by the Institution of Civil Engineers, with the award of the 2018 Bill Curtin Medal for Research and Innovation.

4.2 Improved Risk Evaluation

Maximising the efficiency of all UK coastal flood defences

Flood defences are the key element of coastal flood management, with their primary design feature being the sea-wall height. Statistical methods for estimating the sea-wall height to give the intended level of protection are required, with the estimated height typically larger than any event already observed. Both still water level extremes and overtopping from waves need to be accounted for, so the relevant underpinning research [3.6] and [3.1] respectively are key. Use of theoretically valid models with optimal inference methods are critical for efficient inference: major economic and societal benefits arise from optimising sea wall height, and the large budgets involved result in considerable implications for inefficient estimation of this wall height. The EA's Modelling and Forecasting Scientist, points out that: *"… the cost sensitivity to over-design by 1m would therefore be around GBP1.65billion. Under-design, on the other hand, would result in an increased risk from flooding … over GBP1billion per annum)"* [5.3]. HM Government's 2018 report on environmental coastal flood boundary conditions for the UK gives a sense of importance of the statistical analysis estimates for still water levels: with new data updates and with method improvement these can differ from earlier values by 20-30cm [5.8].

The EA specified that the industry standard for sea walls heights in all new UK coastal flood designs over the period 2014-20 were to be the values estimated using the statistical methods developed by Tawn [5.3]. HR Wallingford estimate that these methods have led to ***over GBP75million of savings for the UK Government and over GBP1billion for the nuclear industry since*** [5.2]. The EA indicates that these estimates have also saved the UK Government GBP8million from consultant fees since 2014 (GBP20,000 per scheme for 60 schemes per year) [5.3].

The evolution of statistical methods for these new design levels has been in two stages. First, Tawn provided the sole statistical expertise in a multi-disciplinary consortium with JBA, the National Oceanography Centre (NOC) and Dutch engineering consultancy Royal Haskoning using the novel modelling framework based on skew surges extremes [3.6,5.3], with these estimates forming the industry standard from 2014 to 2018. Second, Tawn developed a number of major inferential improvements to this skew surge model [5.8] (reported in [5.3]). The resulting updated estimates have become the new industry standard from 2018. The EA identify this work as "*internationally pioneering and there has been much interest from other nations in using the codes and science development*", also noting that with "*the codes freely available internationally*" this enables broader impact beyond the UK [5.3].

Catastrophic flood insurance losses

JBA has developed simulations of extreme flood events globally using extensions of [3.1-3.4] for use by insurers and reinsurers within 'catastrophe models.' As reported by the Executive Chair of JBA, these products support industry "*needs for portfolio risk analysis to meet business planning and regulatory compliance requirements*." The products have been "*licensed by more than 30 major re/insurance clients internationally. Our data are available in all territories around the world through the Oasis Loss Modelling Framework, an open catastrophe modelling platform that brings our data to a community of over 100 partners. Users of our event set data include the UK's Government-backed flood reinsurance company, Flood Re, and the French state-owned reinsurance company, CCR.*" [5.1].

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

[5.1] Letter from Executive Chair JBA Group. Corroborating the use of [3.1-3.3] in work at JBA for use by: NFFR, NRA and by the insurance sector.

[5.2] Letter from Chief Technical Director, HR Wallingford. Corroborating the use of [3.1] in work at HR Wallingford for use by NRA.

[5.3] Letter from Modelling and Forecasting Scientist, Environment Agency. Corroborating Tawn's pivotal role in [3.6] for updating the UK coastal flood boundary conditions.

[5.4] HM Government: National Flood Resilience Review - 2016. Corroborating use of [3.1-3.5].

[5.5] Letter from Sir Mark Walport FRS FMedSci, Chief Scientific Adviser to HM Government and Head of the Government Office for Science, corroborating Tawn's critical input to NFRR [5.4].

[5.6] HM Government: National Risk Assessment/National Risk Register of Civil Emergencies – 2017 Edition**.** Corroborating evidence: The report uses [5.8] and hence [3.1-3.3].

[5.7] Environment Agency (2017). Spatial joint probability for flood and coastal risk management and strategic assessments: SC140002. Corroborating use of [3.1-3.3] and their input to [5.7].

[5.8] HM Government: Environmental Coastal flood boundary conditions for the UK: 2018 update. Corroborating [3.6] input to this industry standard methodology and set of design values.

[5.9] Environment Agency: (2020) National flood and coastal erosion risk management strategy for England: executive summary. Corroborating source of flood risk data.