Institution: Lancaster University

Unit of Assessment: 7, Earth Systems and Environmental Sciences

Title of case study: Transforming Government assessments of flood risk and resilience through improved understanding of uncertainties in flood risk modelling.

Period when the underpinning research was undertaken: 2004 to 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Rob Lamb	Professor in Practice	27/05/2015 - present
Keith Beven FRS, NAE	Professor Emeritus	01/09/1985 - present

Period when the claimed impact occurred: August 2013 to December 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

Improved flood risk modelling based on research on risk and uncertainty at Lancaster has been applied across the UK to provide the Government and its agencies with a more realistic understanding of inland flood risk, from catchment to national scales. Consequently, applications of these models helped to justify a four-fold increase in temporary flood defences in England since 2015 (total spend GBP12.5 million), whilst also supporting a longer programme to better protect 300,000 homes, representing a GBP2.3 billion investment. This improved understanding of flood risk and resilience has protected life and assets and has positively impacted the well-being of those at risk. These impacts remain at the centre of flood risk management across the UK and have informed the next generation of approaches for catchment management and the inclusion of flood risks in the UK National Risk Register.

2. Underpinning research

Recent flood events in 2000 to 2001, 2007, 2013 to 2014, 2015 to 2016 and 2020 have each cost the UK between GBP0.5 billion and GBP4.2 billion in economic damages (adjusted to 2019 prices), and together claimed 27 lives and flooded more than 90,000 households. The Environment Agency (EA, the Government's lead flood management authority in England), estimates that more than GBP1.0 billion should be spent annually over the next 50 years to sustain and improve the country's flood resilience. To be effective and cost-beneficial, this investment must be founded on a robust and realistic understanding of flood risk.

Since 2000, Distinguished Prof Keith Beven and Prof Rob Lamb (eligible to be returned as Category "C" staff prior to 27th May 2015) have developed methods to improve the realism of flood models and the resulting risk assessments. Their vision encompassed uncertainty as a fundamental feature, as well as spatial coherence, which represents the explicit spatial connections among places at multiple scales. This work builds on catchment modelling at Lancaster Environment Centre (LEC) led by Beven since the late 1980s. Since 2000, Beven and Lamb (with other co-authors) have published 297 papers attracting 6672 citations. The research since 2000 is categorized into three distinct but overlapping themes: **[2.1] uncertainty constraints; [2.2] spatially coherent models;** and **[2.3] next-generation flood risk information systems.**

2.1 "Models of everywhere" to constrain epistemic (knowledge) uncertainty

In 2007, Beven introduced the concept of "models of everywhere" [3.1], denoting a paradigm in which environmental models (which include models of hydrology and river hydraulics applied for flood risk management) are fundamentally tools for "learning about places [and] should be implemented within a framework of uncertainty estimation". His analysis of uncertainties in flood risk modelling was based on a taxonomy of random (aleatory) and knowledge (epistemic) error types [3.2]. Aleatory uncertainties describe the randomness of measurements or unpredictable events, like the timing or size of a flood; epistemic uncertainties relate to lack of knowledge, such as erroneous models or assumptions. A key conclusion of 3.2 and 3.5 was that epistemic uncertainties in flood risk mapping should be localised and constrained by treating flood models adaptive tools for learning about places, which potentially co-exist across different scales (that is, as models of everywhere).

Working with Lamb, Beven further argued for a place-based approach to the incorporation of uncertainty in models at the floodplain (m to km) scale in [3.3], and that epistemic uncertainties in a flood risk model can and should be constrained through engagement with knowledgeable stakeholders, such as local authority flood managers and drainage engineers.

2.2 Spatially coherent models of aleatory (random) uncertainty about extreme floods
The local models discussed in [3.2, 3.3] can be aggregated to assess the annual average flood risk, which is useful for investment planning. However, understanding the risk posed by any specific extreme flood event, and hence a stakeholder's resilience against that risk, involves consideration of aleatory uncertainties regarding the probability of such an event occurring, and its geographical size and pattern (or "footprint").

Lamb's research focussed on this uncertainty at large scales, extending developments in extreme value theory by statisticians at Lancaster to create a new way of assessing the probability of spatially coherent flood events at national or regional scales [3.4]. Lamb's approach built on a conditional probability model for multivariate extremes, which he extended to address the challenges in modelling flood risk. The extensions addressed the high dimensionality of the flood risk problem, with [3.4] demonstrating analysis of the joint probability of extreme river flows over 148 dimensions (145 river gauges and 3 tide gauges), whereas previous approaches to joint probability in flood management were limited to three dimensions. The approach also improved on earlier models by capturing the complex statistical relationships within the observations more realistically, including correlations that vary in strength both with geographical distance and with the severity of flooding. In [3.4], Lamb showed that the less realistic assumptions made in earlier models would produce biased flood risk estimates. He also introduced a new simulation procedure to generate spatially coherent extreme flood events that were statistically consistent with historical observations, whilst extrapolating plausibly to produce events more extreme than any historically observed flood.

2.3 "Models of everywhere" revisited in next-generation flood risk information systems
In 2019 Beven and Lamb revisited their earlier work with JBA [3.3] in collaboration with a team of digital technologists (computer and data scientists, software engineers and digital designers) at Lancaster. This research [3.5] analysed the technological readiness of the "models of everywhere" concept and found that unlike when the concept was first published in [3.1], there were no longer major technological barriers to implementation at scale. Concurrently, Lamb worked in partnership with the EA and five other external stakeholders to critically re-assess flood risk modelling from the perspective of contemporary trends in data science and technology. This work demonstrated a novel technology stack that explicitly integrated more realistic representations of flood risk within an agile, multi-stakeholder development process [3.6].

3. References to the research
[3.1] **Beven KJ** (2007) Towards integrated environmental models of everywhere: Uncertainty, data and modelling as a learning process, *Hydrology and Earth System Sciences*, [142 citations]
[3.2] **Beven KJ** & Alcock RE (2012) Modelling everything everywhere: a new approach to decision-making for water management under uncertainty, *Freshwater Biology*, [84 citations]
Summarises research by Beven funded through the EPSRC Flood Risk Management Consortium (GBP12.5 million, 2004 to 2012, grant ref EP/FP202511/1, co-funded by Defra, the Environment Agency, UKWIR, OPW Ireland, NI Rivers Agency) and NERC Catchment Change Network (GBP700,000 over 3 years from June 2009 to November 2012).
[3.3] **Beven K**, Cloke H, Pappenberger F, **Lamb R**, Hunter N (2015) Hyperresolution information and hyperresolution ignorance in modelling the hydrology of the land surface, *Science China Earth Sciences*, [50 citations]
[3.4] **Lamb R**, Keef C, Tawn J, Laeger S, Meadowcroft I, Surendran S, Dunning P, Batstone C, 2010. A new method to assess the risk of local and widespread flooding on rivers and coast. *Journal of Flood Risk Management*, 3 (4), 323-336. [60 SCI citations]

[3.5] Blair G, **Beven KJ**, **Lamb R**, Bassett R, Cauwenberghs K, Hankin B, Dean G, Hunter, N., Edwards L, Nundloll V, Samreen F, Simm W, Towe R (2019) Models of Everywhere Revisited: A Technological Perspective. *Environmental Modelling and Software*, 122, 104521
[3.6] Towe R, Dean G, Edwards E, Nundloll V, Blair G, **Lamb R**, Hankin B, Manson S (2020) Rethinking data-driven decision support in flood risk management for a big data age, *Journal of Flood Risk Management*, 13:e,12652.
Citations from Scival

4. Details of the impact

4.1 Practical guidance on uncertainty in flood risk management

Beven and Lamb's research on uncertainty since 2000 has improved flood risk management practice across the UK as evidenced by citations in 30 practitioner or policy reports [5.1], including government strategies for England, Scotland and Wales, evidence reports and policy updates. Of these reports, 12 were co-authored by Beven and/or Lamb. Beven's research (as summarised in [3.1] and [3.2]) drove the development of Good Practice Guidelines within the EPSRC Flood Risk Management Consortium (FRMRC) and reached more than 200 stakeholders through the NERC-funded Catchment Change Network (from 2009 to 2012). Outputs from the FRMRC that cited [3.2] included guidance on assessing uncertainty in flood risk mapping, co-authored by Beven and Lamb, and published in 2014 by CIRIA, widely regarded as an authoritative provider of good practice guidance for the construction and built environment industries (CIRIA Guide C721, included in [5.1]).

4.2 Improving national flood risk models with local knowledge

Beven and Lamb's research on environmental "models of everywhere" was adopted by their industry partner JBA, one of the UK's leading flood risk management specialists, to improve national flood risk maps required by the government under the Flood and Water Management Act 2010. Paper [3.2] describes how JBA applied the models of everywhere concept by implementing a quality assurance portal for its flood models, which enabled local stakeholders to correct epistemic errors (by adjusting the JBA models) in the high-resolution (approximately 2m) national surface water flood risk maps they have produced for government agencies in the UK. A letter from the Environment Agency [5.2a], which in 2013 procured the maps from JBA in England for its Risk of Flooding from Surface Water (RoFSW) mapping, corroborates the importance of the local model corrections in delivering robust flood risk information at a higher level of detail than before. From 2017 onwards, Lamb and Beven's interdisciplinary work with computer scientists, data scientists and technologists has further influenced the 2nd generation National Flood Risk Assessment (NaFRA2) in England. The NaFRA is used by the EA to target investment in flood mitigation measures, to support their funding submissions to the Treasury and to communicate flood risk to the public. Existing versions of NaFRA suffer from being fragmentary in their approach to reconciling risk information from flood models developed at different scales. A letter from the EA [5.2a] corroborates that Lamb and Beven's research (reported in [3.5] and [3.6]) "*has underpinned the design of our once in a generation national flood risk assessment replacement (NaFRA2)*" was influential in the EA's design for NaFRA2 by "*testing of methods and technologies*" to overcome this previously fragmentary approach. Although the research in [3.6] did not appear in a journal paper until 2020, [5.2a] confirms that it had already, since 2017, "*directly influenced*" the EA's thinking whilst designing the NaFRA2 solution, which they describe as "*one of our most significant modelling investments*", including an GBP8.0 million commercial contract [5.2b].

4.3 Improving the government's understanding of extreme flood events

Lamb's research to extend and apply novel statistical methods to model the spatial joint probability of extreme river flows and rainfall [3.4] improved the Government's appreciation of flood resilience at a national scale following severe floods in 2013 to 2016, and changed the representation of risks in the National Security Risk Assessment (NSRA), which underpins central government emergency planning. It also changed the Government's view of risk in the River Eden catchment, and it's understanding of how open data can be used to better protect people from flooding.

After damaging floods occurred in many parts of the UK between 2013 and 2016, the Government established a National Flood Resilience Review (NFRR, [5.5]) "*to assess how the country can be better protected from future flooding*". The NFRR was based on evidence from a Scientific Advisory Group (SAG), chaired by the Government's Chief Scientific Adviser, Sir Mark Walport. Lamb was invited to join the SAG based on his research in [3.4] and related applications to the NSRA, which were on-going at the time and will be described further below. Drawing on the SAG's evidence, the NFRR committed the Government to GBP12.5 million of spending on new temporary (i.e. mobile) flood defences, raising their number four-fold compared with 2015, as announced in Parliament and reported by the BBC [5.4a,b], whilst supporting the Government's on-going capital spend of GBP2.3 billion to protect 300,000 homes [5.4a]. Lamb's work in [3.4] was cited in the NFRR as "*a method developed at Lancaster University and JBA*" [5.5, p.12], 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*", hence motivating further immediate action to improve the flexibility of national flood defences. This improved understanding of flood risk was recognised by the London School of Economics in its response [5.7] to the NFRR, which stated that *"… [the Government] deserves credit for admitting that Ministers have previously misunderstood and significantly under-estimated the probability of flooding*." [text removed for publication]

The Government plans for civil emergencies by maintaining a National Security Risk Assessment (NSRA), which is designed to compare and prioritise all major disruptive risks to national security over the subsequent five years. Prior to 2019 the NSRA was known as the National Risk Assessment (NRA), and this abbreviation will be used in what follows. The full risk assessment is classified, but there is a public-facing summary called the National Risk Register (NRR). The EA's letter [5.2a] confirms that Lamb's research at Lancaster, and subsequent applications by JBA, underpinned improvements in the 2017 NRA. The inland flooding scenarios that drove these improvements were developed in a project commissioned by the EA in which JBA applied the research in [3.4], which was extended and scaled to include all suitable river and rain gauges across the country (more than 1000 in number) and which *"changed the representation of flood risks for the public facing National Risk Register (NRR) and the Cabinet Office's National Risk Assessment"* [5.8]. Based on this extended application of [3.4], the Environment Agency announced [5.8] that *"the National Risk Register now includes a new risk on widespread surface water flooding over a major city. The existing widespread river flooding scenario has been improved and provides a stretching, yet plausible planning assumption for national emergencies."*

Lamb's work on modelling the joint probability of spatial extremes [3.4] was also combined with surface water flood risk models produced by JBA and incorporated local corrections for epistemic uncertainty discussed above in Section 4.2. JBA combined these models to win the top prize in a Defra innovation competition in recognition of their use of Defra's open data in "*innovative ways to tackle flooding focusing on the Eden catchment in Cumbria"* through *"the use of new data and whole-catchment modelling to generate a much wider range of realistic extreme event scenarios than is normally used"* [5.3a]. The winning report [5.3b], co-authored by Lamb and citing [3.4], further influenced Defra's approach to flood risk management in Cumbria and beyond, with the Floods Minister Thérèse Coffey stating [5.3a] *"We will now be able to use these new ideas and insight to help better protect not just Cumbria's people, businesses and infrastructure from flooding but communities across the nation".*

5. Sources to corroborate the impact

[5.1] UK Flood Risk and Resilience Practitioner reports since 2013: Beven and Lamb citation analysis

[5.2] (a) Letter from Theme Leader of the EA Flood and Coastal Risk Management R&D Programme, dated 22nd January 2021. Corroborates impact of research on EA in the Risk of Flooding from Surface Water mapping from 2013, the 2017 National (Security) Risk Assessment and the design of the National Flood Risk Assessment 2 from 2017. (b) Press release by Jacobs citing commercial value of NaFRA2 contract at GBP8.0 million.

[5.3] (a) Press release by Defra, dated 31st January 2017. Official announcement showing JBA/Lancaster University winning the top prize in the "River Eden flood management open data innovation competition" and (b) A copy of the winning report "A Whole Catchment Approach to Improve Flood Resilience in the Eden" dated January 2017, co-authored by Lamb and citing [3.4] on page 13.

[5.4] (a) UK Parliament Statement. Written Statement UIN HLWS139 on the National Flood Resilience Review made by Lord Gardiner, 8th September 2016. Corroborates GBP12.5 million of spending on new temporary (i.e. mobile) flood defences and a GBP2.3 billion investment to better protect 300,000 homes. (b) BBC News Article Hundreds of key sites in England at Risk of Floods, dated 8th September 2016 corroborating GBP12.5 million investment means four times as many temporary flood barriers than in 2015.

[5.5] HM Government: National Flood Resilience Review (NFRR), September 2016. Corroborates aims of the study in the Ministerial Forward and acknowledges Lamb's work on page 12.

[text removed for publication]

[5.7] Press release by the London School of Economics in response to NFRR dated 8th September 2016. Corroborates quote in section 4 that the Government has previously under-estimated the probability of flooding.

[5.8] Environment Agency "Planning for the risk of widespread flooding: Project Summary SC140002/S". Corroborates new risk of widespread surface water flooding over a major city has now been included in NFRR.