Institution: Lancaster University

Unit of Assessment: UoA7 – Earth Systems and Environmental Sciences

Title of case study:

Societal and economic benefits from improved flood modelling based on pioneering Lancaster research in to risk and uncertainty in environmental modelling.

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

Improved flood risk modelling based on the application of research led by Keith Beven at Lancaster has had global impacts in improved flood defence policies and planning by governments, and in assisting insurers with their underwriting (for example in pricing and policy decisions). The benefits are not just financial – they are human too: improved understanding of flood risk and resilience protects life and assets, and has a positive impact on the well-being of many of those at risk. These impacts are at the centre of flood risk management across the UK, are being applied in nine other European countries, and now becoming the methods of choice for flood mapping in developing countries such as Thailand.

2. Underpinning research (indicative maximum 500 words)

The Lancaster Environment Centre (LEC) has been at the forefront of modelling catchment hydrology for several decades, based on fundamental research led by Prof. Keith Beven (1985-present). The impact described in Section 4 is based on the application of Beven's pioneering research in computer modelling for hydrological prediction. Impacts have been achieved especially through the development of the Generalised Likelihood Uncertainty Estimation (GLUE) approach, which required innovative methods to implement the computationally demanding Monte Carlo simulation at its core and, with Prof. Peter Young, Data Based Mechanistic modelling techniques for adaptive probabilistic real-time forecasting. The application of computationally intensive modelling has proved especially valuable in river catchment management. It enables realistic modelling of phenomena such as water quality and flooding, in combination with the methods needed to assess risk and uncertainty that attempt to deal with the sources of error in testing models more explicitly than traditional statistical methods (e.g. see references 1 and 2, Section 3). Early applications included novel analysis of uncertainty in flood-plain inundation models (reference 3). Between 1993 and 2012, research in this area has attracted research funding totalling approximately £4.5M and supported c. 18 PhD projects.

Beven and his co-workers recognized that the effective application of models for risk and uncertainty assessments in the environmental sciences required the application of then state-of-the-art advances in computing power. That insight led Beven's team to pursue the innovative use of parallel computing techniques emerging from the domain of High Performance Computing into hydrological modelling, an advance which underpinned numerous academic publications (see for example references 4-5 in Section 3). This early work laid the foundation for the later realisation by one of Beven's students that computing systems designed for video gaming could be adapted cheaply to overcome computational constraints on two-dimensional flood inundation models used for flood risk management (see Section 4). There is on-going iteration between Beven's fundamental research (e.g. reference 6) and its application by government and industry stakeholders, which continues to enhance impact. Beven led the Risk and Uncertainty component in Phase 1 of the Flood Risk Research Management Research Consortium (FRMRC1) funded by EPSRC, Defra/EA and others (2004-2012), and the GridStix forecasting project within the NERC FREE Programme. Beven also contributed to the Environment Agency SC080030 Probabilistic Flood Forecasting project led by Atkins Global (2008-2010). His role as leader of the Catchment Change Network (a NERC Knowledge Exchange project: 2009-2012) secures an on-going (through ccmhub.net), direct route between LEC's fundamental research and a wide range of stake-holders.

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

** indicates the three references that were most central to the impact that has been achieved.*

1*. Beven, K.J. (1993), Prophecy, reality and uncertainty in distributed hydrological modelling, Adv. in Water Resourc., 16, 41-51. (464 citations in Web of Science)

2. Beven, K J, 2006, A manifesto for the equifinality thesis, J. Hydrology, 320, 18-36 (470 citations in Web of Science)
3. Aronica, G, Hankin, B.G., Beven, K.J., 1998, Uncertainty and equifinality in calibrating distributed roughness coefficients in a flood propagation model with limited data, Advances in Water Resources, 22(4), 349-365. (106 citations in Web of Science)
4*. Lamb, R., K. Beven, and S. Myrabo, (1998) Use of spatially distributed water table observations to constrain uncertainty in a rainfall-runoff model. *Advances in Water Resources*. **22**: 305-317. (now 99 citations in Web of Science)
5*. Beven, K and Freer, J (2001) Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology Journal of Hydrology: **249:** 11-29. (559 citations in Web of Science)
6. Pappenberger, F., and K. J. Beven (2006), Ignorance is bliss: Or seven reasons not to use uncertainty analysis, Water Resour. Res., 42, W05302, doi:10.1029/2005WR004820 (127 citations in Web of Science)

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

LEC's research into catchment and flood modelling has resulted in substantial improvements in modelling hydrological risks world-wide, resulting in significant economic and societal benefits. One of the most important hydrological risks is flooding, which causes huge damage globally, leading to enormous financial and human costs. Flooding is managed through a combination of investment in flood defences, development planning, insurance and emergency or disaster responses. All these activities depend on accurate and detailed flood mapping or real-time forecasts, both based on computer modelling. Governments and insurers require flood models at multiple scales, from national assessments down to local modelling in urban environments. Delivering such models is a significant science challenge because flooding involves many factors that control the occurrence, magnitude and timing of any given event. Lancaster's developments in environmental modelling have been at the leading edge of applying uncertainty concepts to risk models, and have been applied world-wide by a range of end users. However, for this case study we will focus on one specific example in which well-documented impacts delivered by a commercial research user can be directly attributed to Beven's research.

Tools for operational flood forecasting typically predict the depth of water at specific locations on a river, but for planning and insurance purposes it is much more important to have two-dimensional (2D) maps of potential flood risk. To produce the most realistic mapping possible demands 2D dynamic hydraulic flow models, which are computationally very intensive, something that constrained widespread application by industry. However, these constraints were lifted through insights resulting from Beven's research on uncertainty methods which gave a stimulus to apply parallel computing techniques for hydrological modelling (see Section 2). This is summarised in the following timeline of some of the key developments.

1993-1996 Beven's fundamental research on uncertainty methods includes pioneering use of parallel computing in environmental modelling (references 3 & 4 in Section 2), including in PhD research by one of Beven's students, Rob Lamb (1993-1996).

1996. Lamb graduates and maintains links with Lancaster research on risk and uncertainty

2002. Lamb joins JBA, a consultancy working in flood risk management[A] which has its own in-house 2D flood inundation model, JFlow[B].

2005-2007. Drawing on his Lancaster research Lamb exploits mass-market graphics processing units (GPUs, parallel processors designed for computer graphics), allowing JBA to run flood models up to a thousand times faster[C,D].

2006 onwards. JBA successfully apply JFlow GPU (see evidence of impacts below)[D].

2009-2011. Lancaster and JBA demonstrate use of JFlow within the GLUE framework in the EPSRC-funded FRMRC project to produce the first uncertainty-based flood maps, including Google earth visualisations. Workshops run with EA, consultants, and town planning staff under Catchment Change Network to disseminate the advances.

In summary, co-ordinated fundamental and technological advances, driven by Lancaster's pioneering research and Lancaster-trained personnel, were the enabling research that led JBA to develop the world's first commercially successful GPU-based flood model, and Lancaster to produce the first probabilistic flood risk maps. JBA's software system is now being used world-wide[B,C]. While the major impacts of JFlow are undoubtedly on those communities and individuals vulnerable to flooding (see below) it is worth noting the commercial success of JBA as a UK company. Since its formation in 1995, it has grown to become a major employer of environment risk analysts, with more than 50 staff directly employed in applying JFlow through JBA Risk management Ltd[D]. Revenues relating to JFlow are currently around £3 million annually, and the company's annual turnover overall is now approximately £13 million[E]. In 2012, JBA was a finalist for the Royal Academy of Engineers (RAEng) MacRobert Award[F] for innovation, for its use of GPU processing technology in JFlow. This award "seeks to demonstrate the importance of engineering and the role of engineers and scientists in contributing to national prosperity and international prestige". In selecting JBA as a finalist, the RAEng recognised JFlow for "outstanding technical innovation with benefits to the community and commercial success". Know-how gained through Lancaster research was instrumental to this success, which has enabled JBA to become a world leader, modelling more rivers in more locations than any other company, for private clients and government agencies in the UK and elsewhere[D].

JFlow delivers maps and analytical products underpinning many assessments of flood risk in the UK and beyond[F]. In England, the Environment Agency's National Assessment of Flood Risks (NaFRA) 2009 estimates that one in six homes are at risk, with annual damage costing more than £1billion. Following major floods in 2007, Sir Michael Pitt's review included the urgent recommendation for improved flood mapping, in particular for floods caused not by rivers bursting their banks but by overland runoff, and the incorporation of prediction uncertainties into flood forecasting and planning. This type of mapping had not been done comprehensively, partially because of the high computational cost. However JFlow-GPU allowed JBA to produce the first national surface water flood map, which JBA licensed to the Environment Agency[G. "]JBA has subsequently delivered two major updates for the Environment Agency's national surface flood maps[D,H]. JBA also used JFlow for reservoir inundation maps meeting Government's strategic needs under emergency planning legislation, modelling potential impacts from breaching of 2100 reservoirs in the UK[H] – This provides information necessary for public security at one tenth of the cost of alternative modelling approaches also tested[E].

The RAEng noted that "*JBA Consulting's flood risk modelling system, JFlow, has become ... an essential tool for the UK's insurance industry*"[I]. According to JBA, in 2013 "*GPU-based JFlow software is now used by 70% of UK and 80% of Irish Insurers, including the top five UK insurers by market share*[D]. Maps produced using JFlow were described by leading insurer Aviva as "revolutionary"[J]. At a time when many householders face problems obtaining household insurance due to flood risk, a major societal benefit arising from the improved precision and confidence delivered by JBA's use of JFlow has been to allow insurers to qualify more than 600,000 properties in flood risk areas for insurance[K].

With the productivity gains realised through GPU parallel technology, JBA has also been able to develop national flood maps for Ireland, France, Germany, Poland, the Czech Republic, Slovakia, Hungary, Belgium and Luxembourg[C,K]. The lower cost of using JFlow instead of more "traditional" approaches makes it ideal for modelling flood risk in developing countries, where flood mapping has previously been uneconomic. A prime example is the response to major flooding in Thailand in 2011. This was one of the five costliest natural disasters in modern history (with World Bank estimates of USD45.7 billion economic losses and some 1.5 million homes and other buildings affected). JBA "*was able to respond by using JFlow to produce flood maps of the whole country within four months*"[E]. This mapping helped to provide credible information about flood risks that has been taken up by insurers and helps to underpin the market[L]

While JFlow's adoption of parallel computing technology forms a focussed case study of the impact of developments driven by Lancaster's research, there are other cases where our research has been at the leading edge of applying risk and uncertainty concepts to floods and flood risk. One example is the incorporation of Lancaster's flood forecasting methods into the Deltares flood early-warning system[M] that is "... *applied as the primary operational flood forecasting tool used by flood management authorities in basins across the continental United States and Alaska, in England and Wales, Scotland, Ireland, Netherlands, Germany, Austria, Spain, Italy, Switzerland, Taiwan, Pakistan, the Zambezi basin, Ghana, Canada, Colombia, Indonesia, Bolivia and by the Mekong River Commission*"[N]. Impact is still growing, for example new knowledge and understanding is informing new industry user guidance, such as the CIRIA (Construction Industry Research and Information Association) Framework for assessing uncertainty in fluvial flood risk mapping, Report C721 (in press, 2013) and directly to end-users via the Catchment Change Network.[O]

Based on pioneering research, the appointment of LEC-trained individuals to key posts with stakeholders working with the water industry, and on-going collaborative research, Beven's research has delivered the tangible benefits that we anticipate that continue to grow in the future.

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

A. http://www.jbaconsulting.co.uk/

B. http://www.jbaconsulting.com/products/JFlow

C. http://www.intermap.com/Portals/0/doc/Newsletters/RMA_Newsletter_Spring_2010.pdf

D. Letter from the Managing Director of JBA risk management

E. Company data on JBA Ltd.

F. http://www.raeng.org.uk/prizes/macrobert/pdf/MacRobertAwardBrochure_2013.pdf

G. Hunter, N, Waller, S, Balmbra, V, Hankin, B, Faulkner, D, Lamb, R, Horritt, M, Wyse, P. (2010) Broad Scale Mapping of Surface Water Flooding - Present Status and Future Improvements, Proceedings of the Environment Agency FCRM>10 Conference, 29 June - 1 July 2010, Telford Conference Centre, Paper O80.

H. Environment Agency (2013), Updated Flood Map for Surface Water, National Scale Surface Water Flood Mapping Methodology, Final Report version 1.0 (May 2013), Environment Agency Bristol.

I. Environment Agency Reservoir Flood Maps: External Guidance (October 2011) http://a0768b4a8a31e106d8b0-50dc802554eb38a24458b98ff72d550b.r19.cf3.rackcdn.com/flho0612bwnn-e-e.pdf.

J. http:/www.aviva.co.uk/media-centre/story/1684/norwich-unions-revolutionary-flood-map-begins-roll/

K. http://www.insurancejournal.com/news/international/2010/05/26/110194.htm

L. http://insurancenewsnet.com/oarticle/2012/03/19/jba-launches-first-flood-model-for-thailand-a-334973.html#.UlvA21DEMqh

M. Letter from Deltares Inland Water Systems - Operational Water Management, Delft, The Netherlands

N. http://oss.deltares.nl/web/delft-fews/implementations

O. http://www.catchmentchange.net/