Institution: University of Bristol

Unit of Assessment: 17 – Geography, Environmental Studies and Archaeology

Title of case study: Flood risk management is strengthened across the world as a result of inundation models developed at Bristol

1. Summary of the impact

A two-dimensional flood inundation model called LISFLOOD-FP, which was created by a team led by Professor Paul Bates at the University of Bristol, has served as a blueprint for the flood risk management industry in the UK and many other countries. The documentation and published research for the original model, developed in 1999, and the subsequent improvements made in over a decade of research, have been integrated into clones of LISFLOOD-FP that have been produced by numerous risk management consultancies. This has not only saved commercial code developers' time but also improved the predictive capability of models used in a multimillion pound global industry that affects tens of millions of people annually. Between 2008 and 2013, clones of LISFLOOD-FP have been used to: i) develop national flood risk products for countries around the world; ii) facilitate the pricing of flood re-insurance contracts in a number of territories worldwide; and iii) undertake numerous individual flood inundation mapping studies in the UK and overseas. In the UK alone, risk assessments from LISFLOOD-FP clones are used in the Environment Agency's Flood Map (accessed on average 300,000 times a month by 50,000 unique browsers), in every property legal search, in every planning application assessment and in the pricing of the majority of flood re-insurance contracts. This has led to more informed and, hence, better flood risk management. A shareware version of the code has been available on the University of Bristol website since December 2010. As of September 2013, the shareware had received over 312 unique downloads from 54 different countries.

2. Underpinning research

Please note that numbered citations refer to outputs listed in section 3 and lettered citations refer to evidence sources listed in section 5.

Relevant contextual information:
Before laser altimetry terrain data and satellite flood imagery became available in the late 1990s, hydraulic models were tested against data from highly controlled laboratory experiments. Because of the precision of such data, modellers could inevitably prove that building more complex physics into their models incrementally improved the predictive power. As a result, predictive models of the late 1980s and early '90s were complex in terms of the physics equations used and costly in terms of the computer power needed to solve those equations. The breakthrough of Bates and De Roo [1] based on research conducted in summer 1999 was to realise that, for real-world applications, improving terrain data resolution increased predictive capability much more than adding additional physics and that this necessitated building simpler, not more complex, models to reduce the computational cost. Bates and De Roo [1] sought to identify the minimum physics required to simulate dynamic flooding, which then allowed the model to run on the most resolved grid possible over the biggest area.

Nature of the underpinning research findings:
The original flood inundation model equations and structure [1] showed how a simple and efficient two-dimensional flood inundation model could be developed by using the well known Manning equation to solve the flow through each face of a square grid cell. Whilst this approach had been known since 1972, the key innovations made by Bates and De Roo [1] were: (i) to implement the equations on a raster grid to enable the easy and computationally efficient use of high-resolution airborne laser scanning terrain data that were then becoming available; (ii) to validate the model rigorously using satellite radar and aerial photo images of flood extent; and (iii) to benchmark the model performance against both simpler and more complex process representations.

Previous studies had failed to prove that a flood inundation model based on the Manning equation was capable of accurately simulating inundation as well as, or better than, more complex codes and this had restricted widespread uptake of the idea. Moreover, Bates and De Roo [1] proved that models simpler than LISFLOOD-FP could not be guaranteed to work in all circumstances and that the formulation they developed was the simplest model capable of simulating floodplain inundation.

Over the next decade, and keeping minimum acceptable complexity as a fundamental design criterion, LISFLOOD-FP was improved in a number of ways:
- In 2001 an order of magnitude increase in computational efficiency was achieved through the implementation of a flux limited numerical solution in LISFLOOD-FP (model version 1.0) [2].
- In 2005 a major update (to version 3.0) led to correct predictions of dynamic wave propagation when compared to analytical solutions of the shallow water equations through the addition of an unconditionally stable adaptive time-step equation [3]. This update solved problems identified with the flux-limiter approach, but came at higher computational cost – significantly so in the case of the fine spatial resolution grids necessary for urban inundation modelling [4].
- Further improvements in computational efficiency were made in 2010 through parallelisation of the model code (model version 4.0) on both shared memory and distributed memory architectures [5]. This led to a parallel efficiency of 0.7 when the model was run on 100 cores, which raised speeds 70 times compared to those achieved with a serial version of the code.
- In 2010, the Manning equation flux calculation was replaced by a simplified formulation of the shallow water equations (version 5.0), which not only provided a better physical representation but also allowed the model to run 10-1000 times faster than version 3.0 of LISFLOOD-FP [6]. This makes possible whole-city-scale simulations at the native resolution of LiDAR data (1- 2m) in reasonable time frames. Such a capability has long been the holy grail of inundation modelling [see 4] and was achieved for the first time by LISFLOOD-FP model version 5.0.

Products of the underpinning research:
- Research outputs 1, 2, 3, 5 and 6 contain complete blueprints for the model, which allow other developers to implement the equations, numerical scheme and model structure.
- A shareware version of the model was made available on the University of Bristol website in December, 2010. As of June 2013, it had received 312 downloads from 54 different countries.

Key researchers and their relative contributions:
The initial code for LISFLOOD-FP was developed with equal contributions by Bates of the University of Bristol and De Roo of the EU Joint Research Centre. Since then, LISFLOOD-FP has been developed entirely by Bates and his research team at the University of Bristol. Specific contributions were made by: Horritt (PDRA 1998-2005), Hunter (PhD 2001-4, PDRA 2004-7), Wilson (PDRA 2003-5), Fewtrell (PhD 2004-8, PDRA 2008-11), Neal (PDRA 2007-12), Sampson (PhD 2010-13) and De Almeida (PDRA 2011-13). Villanueva and Wright [4,5] from the University of Nottingham developed the TRENT model and worked with Bates to incorporate this into LISFLOOD from 2009-10, but no impacts from this collaboration are claimed here. Other co-authors listed on the publications were research collaborators, but did not work on the code.

3. References to the research

Outputs: The 71 papers published in connection with LISFLOOD-FP have 2120 citations, with Bates and De Roo (2000) having 298 citations alone (Web of Science, as of 14th August, 2013).

[1] Bates PD and De Roo APJ. 2000. A simple raster-based model for floodplain inundation. *Journal of Hydrology* **236**: 54-77. (DOI: 10.1016/S0022-1694(00)00278-X).

[2] Horritt MS, Bates PD. 2001. Predicting floodplain inundation: raster-based modelling versus the finite element approach. *Hydrological Processes* **15**: 825-842. (DOI: 10.1002/hyp.188).

[3] Hunter NM, Horritt MS, Bates PD, Wilson MD, Werner MGF. 2005. An adaptive time step solution for raster-based storage cell modelling of floodplain inundation. *Advances in Water Resources* **28**: 975-991. (DOI: 10.1016/j.advwatres.2005.03.007).

[4] Hunter NM, *et al*. 2008. Benchmarking 2D hydraulic models for urban flood simulations. *Proceedings of the Institution of Civil Engineers: Water Management* **161** (1): 13-30. (DOI: 10.1680/wama.2008.161.1.13).

[5] Neal J, Fewtrell T, Bates PD, Wright N. 2010. A comparison of three parallelisation methods for 2D flood inundation models. *Environmental Modelling and Software* **25** (4): 398-411. (DOI: 10.1016/j.envsoft.2009.11.007).
[6] Bates PD, Horritt MS, Fewtrell TJ. 2010. A simple inertial formulation of the shallow water equations for efficient two dimensional flood inundation modelling. *Journal of Hydrology* **387**: 33-45. (DOI: 10.1016/j.jhydrol.2010.03.027).

Funding: LISFLOOD-FP development has been funded by a series of Research Council and grants to Paul Bates. Since 1998, Bates has received £1,105,000 from NERC, £350,000 from EPSRC and £60,000 from the EU. Individual grant information is available upon request.

Prizes: Paul Bates and co-authors were awarded the 2012 Lloyd's Science of Risk prize for Natural Hazards for the theoretical development of the LISFLOOD-FP model reported in [6].

4. Details of the impact

The blueprint for LISFLOOD-FP has been placed in the public domain through the publications listed in section 3. This has allowed code developers, both academic and commercial, to produce their own versions of LISFLOOD-FP (in effect clones) or implement the equations and algorithms developed at Bristol within their own models. The major beneficiaries have been the flood risk management industry, which operates within the UK as well as overseas, flood risk decision makers and the UK general public. The benefits have been three-fold:

i) LISFLOOD-FP served as a proof of concept for industry:

"Our original 2D floodplain model, JFlow, was closely related to the LISFLOOD-FP model," said Dr Rob Lamb [A], Chief Scientist at the engineering consultancy and risk management company JBA Group. "The LISFLOOD-FP research established a proof of concept for the robust use of relatively simple hydraulic concepts to model flows dynamically on a digital terrain model grid."

ii) It saved developer time:

"The LISFLOOD documentation and published scientific papers have helped RMS to speed up our own 2D flood model development," said Dr Dag Lohmann [B], Vice President of Model Development at RMS Ltd, a risk management consultancy.

iii) It advanced the predictive power of commercial models:

"Based on our analysis to date, we believe, among other things, the implementation of the LISFLOOD-FP algorithm within the flood inundation component of the (England and Wales) national flood risk assessment method will offer a major step change in improvement in the quality of the results of the national flood risk assessment and hence improved decision making," said Dr Ben Gouldby [C], Principal Scientist for the Flood Management Group at HR Wallingford, an engineering and environmental hydraulics consultancy.

Between 2008 and 2013, clones of LISFLOOD-FP have been used by a number of commercial organisations, including:

JBA Group, a leading UK-based engineering consultancy with UK and international markets. JBA have used their clone, JFLOW, to enhance flood risk management globally by:

- developing the world's first national surface water flood risk map (for England and Wales) in 2008 [A];
- developing national reservoir inundation maps (for England and Wales) in 2009 [A];
- conducting regional culvert flood risk assessments (for England and Wales) in 2011 [A];
- producing a flood map of Thailand in 2011 and the first flood map of India in 2012 [A];
- continuing to provide flood risk information through the UK national Flood Map. In 2002, JBA used the original version of their JFLOW model to produce the extreme flood outline on the national Flood Map for England and Wales on behalf of the Environment Agency (EA) [A]. This flood map, hosted on the EA website, continues to be the main official source of flood risk information available to the general public and is used as part of every homebuyer property search and planning decision in England and Wales. Between June 2010 and May 2012, this website averaged nearly 300,000 hits from over 50,000 unique browsers each month [D], a statistic which does not include data requests by phone.

RMS Ltd leads the global catastrophe risk modelling market and sets the standard for quantifying risk [B]. They have used their version of LISFLOOD-FP to develop river flood models for the UK and China, which are industry standards in the insurance industry for underwriting and portfolio management [B] and used in the pricing of the majority of re-insurance contracts in these territories. In 2008, RMS used their model to estimate that one in four British homes were at risk of flooding and £600 billion in residential property value was exposed to flood risk [E] in their response to Sir Michael Pitt's review of flood risk in the UK [F].

Ambiental Ltd is a specialised modelling firm providing flood risk and other mapping information to the insurance industry. Ambiental developed their own proprietary code FlowRoute™, which incorporates some of the LISFLOOD-FP algorithms [G]. "The published material relating to LISFLOOD has assisted my company to enhance the performance of our own FlowRoute™ software and this has had an important impact on our business growth and penetration into new markets," said Justin Butler [G], Managing Director at Ambiental.

In 2010, Ambiental developed flood models for South America that were used by the global reinsurance company, Willis Re, to provide detailed flood risk estimates for Latin America, which helped insurance and reinsurance firms optimise their portfolios in these areas and manage for flood risk [H]. In 2011, they used FlowRoute™ to help Chubb Insurance Company of Europe SE assess the severity of flood risk faced by properties in the UK [I].

A shareware version of the LISFLOOD-FP model, user manual and set of example files were made available to non-commercial institutions and collaborators in December 2010. As of September 2013, the shareware had received 312 unique downloads from 54 different countries. The shareware is being used in diverse ways, and has potentially saved each these researchers from purchasing commercial software that can cost anywhere from a few hundred to tens of thousands of dollars.

As a result of these activities, and specifically for the paper [6] describing the simplified formulation of the shallow water equations used for model version 5.0, Lloyd's of London awarded Paul Bates and co-authors their 2012 Science of Risk Prize for Natural Hazards. In the award citation [J], the CEO of Lloyd's, Richard Ward, stated: "The judges praised the theoretical basis of the paper and appreciated that the research can be practically applied. They were impressed with the open nature of the research and the fact it had already been used in practice."

5. Sources to corroborate the impact

[A] Lamb, R (Chief Scientist, JBA Group). Letter to PD Bates. April, 2012.

[B] Lohmann, D (Vice President of Model Development, RMS Ltd). Letter to PD Bates. April, 2012.

[C] Gouldby, B (Principal Scientist, HR Wallingford). Letter to PD Bates. May, 2012.

[D] Environment Agency. 2012. *What's in your back yard: Floodmap topic,* website statistics (1/06/2010-01/05/2012) provided by Gilbert, D (Digital Technical Officer, EA) in an email to NF Temple. June 14, 2012.

[E] Press release by RMS (June 24, 2008). *One in Four British Homes at Flood Risk, Says RMS* [http://www.insurancejournal.com/news/international/2008/06/25/91311.htm, accessed 23rd August 2013].

[F] The Pitt Review – *Learning Lessons from the 2007 Floods*. Available online at [http://webarchive.nationalarchives.gov.uk/20100807034701/http:/archive.cabinetoffice.gov.uk/pittreview/thepittreview/final_report.html, accessed 15th August 2013].

[G] Butler, J (Managing Director, Ambiental). Email to N Temple. April 26, 2012.

[H] Press release by Ambiental (October 6, 2010). *Willis Re & Ambiental release groundbreaking flood models for Latin America* [http://www.ambiental.co.uk/news/in-the-press/ambiental-news-willis.html, accessed 15th August 2013].

[I] Press release by Ambiental (November 2, 2011). *Ambiental announce new flood assessment capability* [http://www.ambiental.co.uk/news/in-the-press/ambiental-news.html, accessed 15th August 2013].

[J] Ward, R (CEO, Lloyd's of London). Letter to PD Bates October 2012.