Institution: University of Exeter

Unit of Assessment: UoA 11 Computer Science and Informatics

Title of case study: Improving Flood Resilience Through Rapid Cellular Automaton Simulation (CAFlood)

Period when the underpinning research was undertaken: 2010-2018

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:
Edward Keedwell	Professor	2006 - 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

The timely creation of accurate flood models has assumed large-scale significance in an era of climate change. Researchers at the University of Exeter (UoE) developed a cellular automaton flood simulation method (CAFlood) that models flood risk significantly more rapidly than conventional approaches. This method has been adopted by national and international governmental organisations and industries to provide early warning flood forecasting, analyse flood risk at higher resolutions and quantify uncertainties in complex scenarios. Impacts include:

Protecting people, properties and businesses

- £78m potential damage prevented by £3.4m Torbay flood defence investment
- 2.6 million people protected in Taipei City, Taiwan

Benefits to the water, reinsurance and risk assessment sectors

- Improved risk analysis for global reinsurance companies (e.g. MunichRE)
- Reduced water main burst damage by 60% for Thames Water

Influencing policy and risk strategies

- Underpinned the Environment Agency case for scalable flood risk assessment systems
- Developed strategies to protect over 970,000 people in Naples, Italy
- Supported the development of community consensus on the implementation of sustainable land management practices

2. Underpinning research

The underpinning research is based on **Keedwell's** work in developing novel algorithmic solutions to problems in the water sector, including the application of cellular automata to the optimal design of water distribution networks **[3.1]**. Here, the research was carried out by a multidisciplinary team involving **Keedwell** (Computer Science), Savic and Djordjevic (Engineering), together with Chen, Guidolin and Ghimire and three PhD students, Duncan, Austin and Gibson. This EPSRC-supported research (EP/H015736/1, £425k, 2010–2013) investigated a radically different cellular-automaton approach to modelling flood dynamic behaviour over 2D terrain and created a novel cellular automata flood modelling system (CAFlood) implemented for both stand-alone and distributed computing platforms. **[3.2]**.

The approach adapted the well-known artificial life method of cellular automata (CA), previously used to model physical systems, epidemiology and bacterial colonies, to the

problem of flood simulation. The approach makes use of the core CA principles of *localism*, *homogeneity* and *parallelism* coupled with exploitation of modern graphical processing unit (GPU) designs and novel hydraulic modelling approaches to deliver transformational computational efficiency increases that have in turn enabled applications that would not have been previously possible.

The main findings from the research underpinning this impact demonstrated that:

1. The use of cellular automata in the simulation of flooding provides discretization of space and time, which in turn leads to increased speeds of 10-20x over existing flood modelling techniques.
2. The benefits of the cellular automaton approach are amplified when adapted for the architecture of modern GPUs. GPUs lend themselves to the local, distributed computation of a cellular automaton and the intelligent deployment of the native 'lattice' of CAFLOOD models on GPU technologies enables transformational speed increases.
3. The flexibility of the cellular automaton approach provides the mechanism to innovate and optimise cell sizes, shapes and state-transition rulesets to serve a variety of high impact applications in flood modelling.

The research findings were applied to benchmark (Environment Agency benchmarks) and real-world flooding instances (Torbay) to demonstrate the efficacy of the proposed approach and the potential for faster modelling through CA. The results were published in the Journal of Hydroinformatics **[3.2]** and Environmental Modelling and Software **[3.3]**, with the underpinning theoretical work on the GPU acceleration of cellular automata published in the Journal of Parallel and Distributed Computing **[3.4]**. Work on the software framework **[3.5]**, and the potential for automation of state transition rules through genetic programming **[3.6]** were disseminated via international conferences. Furthermore, a PhD was awarded on this topic in 2015 (Gibson; supervisors: **Keedwell** & Savic). In late 2018, follow-on funding of £39K was awarded via a competitive process from the EPSRC Impact Acceleration Account at the University of Exeter to further explore the commercialisation of the CAFlood system.

3. References to the research

3.1 Keedwell E, Khu ST. (2006) A novel cellular automata approach to optimal water distribution network design, *Journal of Computing in Civil Engineering*, volume 20, no. 1, pages 49-57, https://doi.org/10.1061/(ASCE)0887-3801(2006)20:1(49)

3.2 Ghimire, B., Chen, A.S., Guidolin, M., **Keedwell, E**.C., Djordjević, S., Savić, D.A., (2013). Formulation of a fast 2D urban pluvial flood model using a cellular automata approach. *Journal of Hydroinformatics* 15, 676. https://doi.org/10.2166/hydro.2012.245

3.3 Guidolin, M., Chen, A. S., Ghimire, B., **Keedwell, E.C**., Djordjević, S., Savić, D.A., (2016). A weighted cellular automata 2D inundation model for rapid flood analysis. *Environmental Modelling & Software*, 84, pp.378-394 https://doi.org/10.1016/j.envsoft.2016.07.008

3.4 Gibson, M. J., **Keedwell, E. C**., & Savić, D. A. (2015). An investigation of the efficient implementation of cellular automata on multi-core CPU and GPU hardware. *Journal of Parallel and Distributed Computing,* 77, 11-25. https://doi.org/10.1016/j.jpdc.2014.10.011

3.5 Guidolin, M., Duncan, A., Ghimire, B., Gibson, M., **Keedwell, E.C**., Chen, A. S., Djordjević, S., Savić, D.A., (2012). *CADDIES: A New Framework for Rapid Development of Parallel Cellular Automata Algorithms for Flood Simulation. HIC2012, Hamburg, Germany.* https://ore.exeter.ac.uk/repository/handle/10036/3742

3.6 Gibson M, **Keedwell EC**, Savic D. (2014) Genetic Programming for Cellular Automata Urban Inundation Modelling, *11th International Conference on Hydroinformatics, New York, 17th - 21st Aug 2014.* https://ore.exeter.ac.uk/repository/handle/10871/21377

4. Details of the impact

Climate change is leading to increased frequency and severity of flooding, and in the UK, damages from flooding and coastal change are already high (estimated at an average of £1 billion per annum (*UK Climate Change Risk Assessment 2017 Synthesis Report: priorities for the next five years (2016; p32)*). The combination of increased extreme weather events and population growth will lead to even greater impacts and globally it has been estimated that by the end of the century coastal flooding events could threaten assets worth up to $14.2 trillion worldwide, one fifth of the global gross domestic product. CAFlood was developed to help mitigate the risks of flooding through accurate modelling of pluvial and fluvial flooding and coupled with a step-change in computational efficiency has resulted in the following impact.

Protecting people, properties and businesses

- ***Securing investment of £3.4m for the Torbay flood defence system, that will protect 3,000 people and prevent up to £78m in potential damage*** **[5.1; 2018]** Torbay Council, as part of an EU Horizon 2020 project (EU-CIRCLE), adopted CAFlood for high-resolution flood risk assessment in Torquay, Paignton and Brixham under multiple current and future climate conditions and was used to evaluate the effectiveness of various adaptation measures. The results provided evidence that flood damage could be reduced from £78m to £0.2m by installing a secondary flood wall, safeguarding more than 3,000 people in 700 households, 330 commercial properties and 165 hotels**.** The uniquely rapid and accurate set of CAFlood simulations was key to Torbay Council securing £3.4m government investment in critical infrastructure to improve resilience against flooding.
- ***200,000 households and over a million commuters benefited*** **[5.2; 2019]** Taipei City Government worked with National Taiwan University (NTU) to build a flood forecasting and early warning system to strengthen the city's response to flooding events. For example, flooding from Typhoon Nari in 2001 claimed 30 lives, affected over 1 million commuters and resulted in losses of over £1billion. Following an evaluation of flood simulation systems, NTU selected CAFlood in 2018 due to its computational efficiency and high accuracy. Collaborating with the UoE, NTU has successfully used CAFlood to inform the early warning system which has transformed the Taipei emergency services approach to flood crisis management. The high accuracy of CAFlood has enabled early warnings to be issued, so that citizens in identified hotspots can take measures to ensure safety (for example through the evacuation of vulnerable residents to emergency shelters or the closure metro station entrances to protect the subway system) and minimise disruption and damage. As a result, the 2.6 million population of Taipei City consisting of over 200,000 households and a million commuters in the Metropolitan Taipei Area are benefitting from this system based on CAFlood.
- ***Other Organisations protecting people, properties and businesses with CAFlood*** CAFlood has been adopted by national and international industries and government organisations for fast flood risk assessment to protect citizens and businesses including organisations in Boston (USA), Bangalore (India), and Khulna (Bangladesh). The Slovenian environment agency (ARSO) has also adopted the software to establish an operational system to provide real-time flood warning for Slovenia. RMS (India) have developed flood hazard layers using CAFlood for area in India, which in turn is being used by insurance companies to provide underwriting solutions. One Concern (USA) have adopted it to establish a scalable urban flood early warning and response system and engineering consultants JonesEdmunds (USA) has also used CAFlood in its development of environmental infrastructure solutions.

Benefits from commercial applications

Industrial commercialisation has been driven by the licencing of CAFlood Pro. The licences, although modest in value, are providing a valuable route for wider application of CAFlood across sectors such as global insurance/reinsurance and the US municipal market.

- ***Flood risk assessment at continental scale for a major global re-insurance industry*** **[5.4; 2015-2016]**
  MunichRE, one of the world's largest reinsurance companies (revenue in 2019 - €51.1bn, in 2017 alone they insured losses due to hurricanes and cyclones to a value of an estimated £135bn worldwide) collaborated with UoE in 2014 to customise the software to meet the needs of large-scale commercial applications. A £51K license and contract research package allowed the development of continental-scale flood models covering thousands of events, such as tropical cyclones, in Asia and Australia, without requiring any additional computational infrastructure. They noted in May 2020 that, *"Since its development, we have made widespread use of the CAFlood model in the framework of the in-house catastrophe modelling setup […] CAFlood made a significant contribution to the competitiveness of our business during this period*". The use of CAFlood by MunichRE benefitted their clients through more accurate and efficient risk analysis and premium calibration, as well as provision of advice for better protection of clients' assets **[5.4]**. Since then, another leading reinsurer, Swiss Re Group, tested CAFlood and confirmed that it was able to improve the resolution of their modelling, enabling a 10x improvement in the speed of their computations **[5.5]**. Also, the US climate risk analytics company, risQ, licensed CAFlood in January 2020 to analyse climate risk for the US municipal market, to ensure that project and investment decisions such as the construction of schools, hospitals or roads, are based on robust risk assessment models. **[5.6]**
- ***Assisting Thames Water prioritise its maintenance strategy, contributing to 60% reduction in properties impacted by water main bursts*** **[5.7; 2014-2016]**
  CAFlood was adopted by an SME, ICS Consulting, through a Knowledge Transfer Partnership (KTP) with UoE, to simulate flooding caused by water main bursts. As a result, ICS secured a £100k contract with Thames Water (the UK's largest water company with 17 million customers) to identify vulnerable locations within London at risk of flooding from these bursts. The 120,000 CAFlood pipe burst simulations took just one week to complete where conventional hydraulic models would have required months. From this information Thames Water prioritised high risk areas in a £247m maintenance programme that has helped drive a 60% reduction in properties affected by large bursts **[5.8]**. In addition to the economic benefits of protecting businesses and infrastructure, this has reduced the health and safety threats to significant numbers of people in London and the surrounding areas.
- ***New Flood Risk Assessment products***
  A new product, Infrastructure Flood Risk Assessment (inFRA) was created in 2018 as an outcome of the KTP with ICS Consulting, using CAFlood as its core engine **[5.7]**. inFRA has added significant additional capability to ICS's consultancy and contributed to their growth. As a result, they were shortlisted for the Water Industry Achievement Awards in 2017. With this competitive advantage, ICS's turnover with existing clients has increased by over £100k per year. inFRA has also led to a £100k contract with Scottish Water, and expansions into new markets in Europe, Canada and the US, which ahead of the Covid-19 pandemic had been expected to contribute an additional £0.5m of annual exports by 2020 (now expected by 2021).

Wider impacts on policy and risk strategies:

- ***Influencing flood risk policies/systems*** (e.g. *National Flood Risk Assessment 2 (NaFRA2)* **[5.9; 2018]**
  The Environment Agency (EA) included the recommendation for a scalable flood risk assessment system in its NaFRA2 business case (2018) based on the demonstrated capability of CAFlood, as acknowledged by the EA's Specialist Technical Input Group.
- ***Strategies to protect over 970,000 people in Naples*** **[5.3; 2019]**
  The Italian government-funded Centro Euro-Mediterraneo sui Cambiomenti Climatic (CMCC) Foundation, adopted CAFlood in a pilot project for flood risk assessment in the city of Naples (970,000 inhabitants). The pilot in 2019 demonstrated the advantages of CAFlood over the CMCC's existing system, saving 3 months and €12,000 for 30

simulations. CMCC have dedicated €40,000 per year for CAFlood applications to investigate flood risk in Naples under future climate change scenarios. The results are enabling CMCC to collaborate with the Municipality to develop adaptation strategies for future flood impact reduction and to protect the public. They plan to extend the application of CAFlood to pluvial flood modelling in other European cities.

- **Engaging communities in the implementation of sustainable flood minimisation approaches [5.10; 2018]**
  CAFlood was fundamental to the Westcountry Rivers Trust (WST) use of serious (educational) games as a tool to facilitate public and policy dialogue on sustainable environmental management. The Cornish village of Millbrook was used a case study, which had suffered from serious floods in 2012, where traditional consultation and engagement exercises did not enable stakeholders to fully understand the cause of the flooding and develop appropriate mitigation strategies. WST developed a game based on high resolution CAFlood simulations with over 432 parameter combinations and used it to engage local residents, including farmers and parish councillors to develop a consensus on effective and sustainable flood management strategies. The CAFlood simulations transformed the attitude of 70% of the participants with regard to sustainable farming and drainage strategies. For WST the "*…outcome has positively influenced the policy-making process in that nature-based solutions have been incorporated into Millbrook parish's flood management strategies…to protect two thousand vulnerable citizens from the impact of flooding*".

5. Sources to corroborate the impact

5.1 Torbay Council Letter

5.2 National Taiwan University (Taipei) Letter

"The high performance and reliability of CAFlood allows us to quickly evaluate citywide flood risk at high spatial resolution, such that hotspot areas can be identified in advance. The system has transformed the emergency services' Standard Operation Procedure for flood crisis management. The model is utilised by our Emergency Operation Centre and gives them a 3 hour window to prioritise response missions to these hotspot areas identified by the model, to actively protect flood threatened areas. The emergency operation centre is now able to deploy its first responders to these high risk areas, to set up temporary defences and pumps to reduce flood levels. This safeguards critical infrastructure and lifeline services. For example, flood gates can be closed at the entrance of metro stations to protect the subway system."

5.3 CMCC Foundation Letter and a video

5.4 Munich RE Letter

5.5 Swiss Re Letter and Memorandum of Understanding

5.6 risQ licence agreement

5.7 ICS Consulting Ltd Letter and KTP report

5.8 Thames Water Annual Performance Report 2016/17 https://tinyurl.com/y2hogawb

5.9 Environment Agency, 2018, National Flood Risk Assessment 2 (NaFRA2)

5.10 Westcountry Rivers Trust Letter