Institution: Cardiff University

Unit of Assessment: Engineering (12)

Title of case study: Improving international flood risk management and hydro-epidemiological modelling strategies

Period when the underpinning research was undertaken: 01/01/2010 – 31/12/2018

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:
R Ahmadian	Reader	15/02/2010 - present
R Falconer	Professor	01/09/1997 - 30/09/2018
C Wilson	Reader	26/03/2001 - present
E Follett	Royal Academy of Engineering- Sêr Cymru Research Fellow	27/08/2018 - present

Period when the claimed impact occurred: 01/08/2013 – 31/07/2020

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

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

Flood waters pose a major risk to property, public health, and in extreme events loss of life through direct floodwater inundation and high currents. Research at Cardiff University applied fluid mechanics methodologies to flood modelling software, which was taken up by industry and government stakeholders to facilitate planning and reduce the hazards to health. Jacobs Engineering Group Inc. used the methodologies to underpin solvers in their Flood Modeller Pro commercial software. This is used by over 25,000 users in more than 150 countries across the world to assess flood risks for a variety of infrastructure projects. In addition, the Cardiff team's modelling of faecal indicator organisms in water assisted local authorities across the UK and changed regulatory authority processes within the Environment Agency.

2. Underpinning research (indicative maximum 500 words)

Accurate modelling of floodwater flow processes allows stakeholders to minimise the risks from flood events, and the biological contamination they frequently carry. The Hydro-Environmental Research Centre's (HRC) flood modelling research focused on two interconnected strands, including:

1) the development of methodologies for applying Alternating Direction Implicit (ADI) and Total Variation Diminishing (TVD) solvers for modelling tranquil and extreme flood events;
2) the transport of bacteria from upper catchments of river and coastal basins to the coast, focusing on improved biological and morphological process interaction modelling.

2.1. Simulations for flood modelling

Predictions of floodwater during extreme events, such as flash floods and dam-break flows, need to match actual flooding scenarios for effective planning and response. Flood modelling can be produced in three general ways: (i) 1D modelling where water flow in rivers and floodplains is modelled in one dimension; (ii) 2D modelling for more complex flow patterns in two dimensions; and (iii) linked 1D and 2D models: where the river flow is generally 1D and the floodplain and urban flow configuration is 2D.

Building upon a previously developed 2D ADI-based numerical solver in collaboration with CH2M Ltd (acquired by Jacobs Engineering Group Ltd in 2017), the Cardiff team investigated new flood models. In 2006 the Cardiff team developed an efficient 2D TVD-based numerical scheme for solving shallow water equations for environmental flows. The resulting model was applied to a hypothetical dam-break scenario, an experimental dam-break case and a physically modelled extreme flooding event, with the predictions comparing favourably with the experimental measurements **[3.1]**. Subsequently this model was extensively refined to

include a range of recent research and development studies, including predicting the forces and stability of vehicles and people in floods and evaluating optimised emergency exit pathways for emergency services **[3.2]**.

Although 1D flood modelling is simpler and faster, the detailed spatial inundation maps and velocity fields of 2D models are more accurate and potentially critical in certain cases such as hazard assessment, but can require prohibitively long processing times. Accurately linking 1D and 2D flood modelling methods is therefore of critical importance to achieve the best balance between speed, accuracy and the level of detail of the results for modelling large areas. Cardiff research compared the commonly used 'water-level' and 'discharge' methods of linking 1D and 2D models. The research demonstrated that the discharge modelling was more consistent across ADI and TVD solvers, indicating increased accuracy of predictions **[3.3]**.

Cardiff model simulations for short steep river basins showed the need to include significantly more complex shock capturing models to predict peak flood elevations and inundation extent, with the flood hydrograph peak only being preserved through such modelling procedures. This research provided a threshold of the bed slope which indicates when specific flood modelling criteria are most appropriate and accurate **[3.4]**.

2.2. Modelling Faecal Indicator Organisms

A new improved framework was developed to apply the principles of combined 1D/2D flood modelling to accurately predict the spread of Faecal Indicator Organisms (FIOs), such as *E.coli*, through bathing water and aquaculture sites, in order to understand the source of pathogens. As part of the NERC Cloud to Coast Project **[G3.1]** the Cardiff team evaluated the role of FIOs in the Fylde Coast, near Blackpool. The team incorporated new models, based on extensive experimental data, to accurately represent the diffusion and transport of bacteria, the decay rate depending on temperature, sunlight and salinity, and the adsorption and desorption onto sediment, showing that this sediment coupling is critically important to the transport of bacteria. This was the first time such a comprehensive modelling study had been done from catchment to coast in the UK **[3.5]**.

Further work, applying linked 1D and 2D models along the Fylde coast, with particular focus upon the mechanism of faecal bacteria transport and decay through the deposition and resuspension of suspended sediments, was undertaken. The analysis was applied to model *E.coli* in coastal bathing waters resulting from management scenarios, including extending outfalls further out to sea. The analysis determined that extending the outfalls was the most effective method of reducing *E.coli* **[3.6]**.

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

[3.1] Liang, D., Lin, B., **Falconer, R.A.** (2007) Simulation of rapidly varying flow using an efficient TVD-MacCormack scheme. *Int J Numer Methods Fluids* 53 (5), pp.811–826. DOI: 10.1002/fld.1305

[3.2] Whittaker, P., **Wilson, C.**, Aberle, J. (2015) An improved Cauchy number approach for predicting the drag and reconfiguration of flexible vegetation. *Advances in Water Resources* 83, pp.28-35. DOI: 10.1016/j.advwatres.2015.05.005

[3.3] Ahmadian, R., **Falconer, R.A.** and Wicks, J. (2018) Benchmarking of flood inundation extent using various dynamically linked one- and two-dimensional approaches. *Journal of Flood Risk Management*, 11(S1), pp.S314–S328. DOI: 10.1111/jfr3.12208.

[3.4] Kvočka, D., **Ahmadian, R.** and **Falconer, R.A** (2018) Predicting flood hazard indices in torrential or flashy river basins and catchments. *Water Resources Management*, 32(7), pp. 2335–2352. DOI: 10.1007/s11269-018-1932-6.

[3.5] Huang, G., **Falconer, R.A.** and Lin, B. (2015) Integrated river and coastal flow, sediment and escherichia coli modelling for bathing water quality. *Water*, 7(9), pp.4752-4777. DOI: 10.3390/w7094752

[3.6] Huang, G., **Falconer, R.A.**, Lin, B. (2017) Integrated hydro-bacterial modelling for predicting bathing water quality. *Estuarine, Coastal and Shelf Science*, 188(15), pp.145-155. DOI: 10.1016/j.ecss.2017.01.018

Selected grant:

[G3.1] C2C Cloud to Coast: Integrated Assessment of Environmental Exposure, Health Impacts and Risk Perceptions of Faecal Organisms in Coastal Waters, NERC grant NE/1008306/1, with University of Sheffield and Aberystwyth. Total funding: £1,762,342, Cardiff total: £399,956

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

The impacts in this case study are focused on two main areas: 1) the integration of Cardiff flood modelling research into commercial software package Flood Modeller Pro; and 2) use of novel Faecal Indicator Organism (FIO) findings by various stakeholders to improve water quality across the UK.

4.1. Flood Modeller Pro

Flood Modeller Pro is a commercial software tool developed by global engineering company Jacobs Engineering Group Inc. (formerly CH2M). Continuing a longstanding collaboration between Cardiff's Hydro-Environmental Research Centre (HRC) and the Flood Modeller Pro developers, Jacobs Engineering Group have continued to collaborate with Cardiff to further improve their software during the current REF period. As stated by Dr Richard Crowder, Director of Water Catchment Management at Jacobs: "*The HRC were able to develop an improved framework for flood modelling, which facilitated improved predictions for extreme flood events. We were able to incorporate these improvements into our commercial software Flood Modeller"* **[5.1]**.

This software has become the main flood modelling suite used by the Environment Agency, Natural Resources Wales and the Scottish Environment Protection Agency, applied within over 500 operational models, including designing flood defences and mitigation plans across the UK **[5.2]**. Flood Modeller Pro has registered over 25,000 users across the world since 1 August 2013 **[5.3]**.

The Cardiff Total Variation Diminishing (TVD) solver and 1D/2D combination methods have been particularly vital in projects which require accurate prediction of fast flowing flood water and for shock events such as dam breaches, levee failures, high-volume flow down spillways or flow over a steep ground/street. The Flood Modeller Pro functionality enabled by Cardiff research has been used on projects around the world, with a selection of projects highlighted by Jacobs **[5.1]**:

- At the request of British Waterways Scotland (now Scottish Canals) Jacobs used the software to analyse breaches of Cobbinshaw Reservoir (Scotland) and assessed direct damages and risk to life, stating that "*we chose the software as the most appropriate tool because of its unique functionality, particularly the Flood Modeller 2D TVD solver*" **[5.1]**. Following this review, Scottish Canals determined that Major Public Safety works were required and undertook leakage repairs in 2018 to safeguard the integrity of the reservoir and manage risk to the wider public **[5.4]**.
- CH2M performed dam-breach modelling using the 1D and 2D solvers within Flood Modeller Pro to confirm hazard classification of the Lane City Reservoir dam and developed dam-failure inundation maps for an Emergency Action Plan for the Lower Colorado River Authority (LCRA), USA. CH2M assisted the LCRA to use the models at the preliminary design stages to compare alternatives and refine designs, which in their final report the LCRA described as "important in evolving the design and moving the process forward efficiently by freezing key design decisions" **[5.5**, p12**]**. By optimising reservoir operations, the LCRA predicts that the new reservoir will add 1 million m^3 of firm water supply **[5.1]**.
- CH2M used the Flood Modeller 2D solver to develop a model incorporating Lowestoft estuary, Lake Lothing and the Kirkley Stream channel (Suffolk) to map flood risk from

a potential tidal storm surge propagating up the estuary and into Lake Lothing. This was commissioned by Waveney District Council as part of the Lowestoft Flood Risk Management Project, following tidal surge flooding of over 160 homes and businesses in December 2013. The modelling identified that Bascule Bridge was important in reducing tidal levels in the estuary and that Mutford Lock was critical in preventing tidal surge entering the Broads. These findings were incorporated into public consultations about the Flood Risk Management Strategy, and a third crossing was granted development consent by the Secretary of State for Transport on 21 May 2020 **[5.6]**.

- The Cardiff HRC group also advise UK industry on application of their solvers within Flood Modeller Pro. Wallingford HydroSolutions are a UK-based water management consultancy who employ the software for their clients. The Director of Wallingford Hydro Solutions, Paul Blackman, wrote that collaboration with Cardiff helped them to "*maximise the benefit of Flood Modeller Pro*", particularly the HRC's experience linking 1D and 2D solvers for complex issues **[5.7]**. Blackman provided two examples of HRC's support. First, the solvers were applied to model the flood risks of the Ebbw River near Newport, which were then used to update the area Flood Map for Natural Resources Wales. Second, solvers were applied to a planned housing development in Bromsgrove, Worcestershire. Blackman wrote that Cardiff's work was used to demonstrate the safety of a proposed development in a high-risk flood area, which was then used to *"ensure the design of any appropriate housing layout"* **[5.7]**. Blackman continued to state that the collaboration with Cardiff recently led to a project with the Chinese government and "*introduced our company to a wider base, enhancing our visibility and market opportunities*" **[5.7]**.

4.2. Faecal Indicator Organism modelling

Through the NERC "Cloud to Coast" project, Cardiff's HRC have worked with water quality stakeholders to apply their expertise to model sites of water contamination through the presence and flow of FIOs in bathing waters.

a. United Utilities and the North West Coast

The Fylde Coast and Ribble River Basin coastal receiving waters (Lancashire, UK) were failing to meet the EU Bathing Directive 76/160/EC mandatory standards, particularly following storm flow conditions. At the mouth of the Ribble estuary are the Lytham St Anne's and Southport designated EU bathing water beaches. United Utilities (North West Water) had previously invested £500M over ten years upgrading wastewater treatment works with UV disinfection and additional storage, but bathing waters continued to fail to meet the EU Directive with faecal coliform counts some four times over the limit.

Cardiff's identification of bacteria associated with sediment that affects bathing waters was praised by United Utilities; Graeme Forrester, the company's Principal Engineer (Wastewater Modelling) noted that the connection had never been taken into account before, and that "*the significance of this cannot be understated"* **[5.8]**. The findings were introduced into United Utilities' long-term strategy, who described this factor as "*vital for understanding the causes of bathing water quality and the development of measures to improve the quality of bathing waters in the North West*" **[5.8]**.

The implications of the research informed infrastructure projects across the North West as part of United Utilities' Asset Management Plan 6 (AMP6) to improve the water quality of Blackpool beaches **[5.8]**. An example project within United Utilities' AMP6 was highlighted by the Environment Agency, who noted that Cardiff's research findings provided evidence to support the strategy of extending outfalls to protect the bathing waters along the Fylde Coast at Blackpool **[5.9]**. United Utilities have since funded a £150M investment programme to improve water quality in Blackpool and the Flyde Coast area, which included the installation of the Anchorsholme Long Sea Outfall: a 3.75km pipeline transporting wastewater to sea, which was completed in 2019 **[5.10]**. United Utilities are currently preparing their AMP7 strategy and confirmed that they will continue to use Cardiff's research findings to inform their plans for projects between 2020 and 2025 **[5.8]**.

b. Environment Agency and national strategy for England

The Cloud to Coast project **[G3.1]** was supported by Environment Agency representatives on the Strategic Advisory Board. Following the research at the Ribble River Basin, Paul Simmons, Principal Water Quality Officer at the Environment Agency praised the innovative integration of catchment, riverine, estuarine and coastal models **[5.9]**. Simmons noted the research provided the Environment Agency with a better understanding of the importance of remote sources in the catchment which provided *"strong evidence for regulators and stakeholders to [use] when identifying improvement strategies"* **[5.9]**.

As a result, the Environment Agency used Cardiff's research when developing the Water Industry National Environment Programme (WINEP), which defines the improvements and investigations water companies must deliver between 2020 and 2025 **[5.9]**. Submitted in 2018 to all water companies across the UK, the WINEP mandates £5BN of investment by UK water companies, requiring changes to protect and improve at least 6000km of UK waterways, 24 bathing waters, ten shellfish sites, and 1,800 hectares of protected nature conservation sites. It also requires enhancements to nearly 900km of river and 4,276 hectares through wider biodiversity improvements **[5.11]**.

In addition, the Environment Agency highlighted the novel recognition of bacteria associated with sediments as an important source of pollution, and as a result they stated that the modelled predictions of FIOs at the bathing waters *"improved significantly by the inclusion of sediment coupling*" **[5.9]**. This result increased the Environment Agency's understanding of causal links for improving water quality, stating: *"Future bathing water investigations and modelling need to understand the importance of this finding and should consider including sediment coupling as a way of improving their model forecasts"* **[5.9]**.

4.3 Summary

Research by Cardiff HRC improved modelling of flood waters which led to two broad areas of impact. First, the research forms a key part of an industry-leading software tool that is used by private and public organisations worldwide to forecast and counter flooding issues. Second, the research was the first to identify a method of predicting bathing water quality and strategies to reduce contaminant levels, directing multi-million infrastructure projects and defining national strategies for improving water quality.

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

[5.1] Testimonial: Dr Richard Crowder, Director, Water Catchment Management, Jacobs Engineering Group Inc.

[5.2] 'Flood forecasting', Jacobs Flood Modeller website

[5.3] Jacobs Flood Modelling factsheet

[5.4] 'Cobbinshaw Reservoir', Scottish Canals website

[5.5] *Innovative Solutions for Design and Construction of an Off-Channel Reservoir*, Lower Colorado River Authority case study, May 2018

[5.6] The Lake Lothing (Lowestoft) Third Crossing Order 2020

[5.7] Testimonial: Paul Blackman, Director, Wallingford HydroSolutions

[5.8] Testimonial: Graeme Forrester, Principal Engineer (Wastewater Modelling), United Utilities

[5.9] Testimonial: Paul Simmons, Principal Water Quality Officer, Environment Agency

[5.10] 'Anchorsholme Long Sea Outfall', Water Projects Online (11 November 2019)

[5.11] WINEP benefits outlined on GOV.UK