Institution: Cardiff University, School of Engineering
Unit of Assessment: UoA 14
Title of case study: Improved Flood Hydrodynamic, Hazard and Water Quality Model Predictions

1. Summary of the Impact

The Hydro-environmental Research Centre (HRC) at Cardiff University has developed a widely used hydro-environmental numerical model, called DIVAST (Depth Integrated Velocities And Solute Transport). DIVAST addresses the need for more accurate models to predict flood risk and water quality levels for a range of extreme events. The model has been implemented in commercial codes, marketed by CH2M HILL (previously Halcrow), and used in design studies, for example, undertaken by Buro Happold. The impacts of the research are marked environmental, health, economic and industrial benefits. It is used by major organisations around the world on large-scale projects and, in particular, for mitigation planning against national and international risks associated with floods and water quality.

2. Underpinning Research

The original hydrodynamic version of DIVAST was developed by Prof. Falconer (Hyder (1997-00) and CH2M HILL (2000-date) Professor of Water Management since 1997). It has been refined by Falconer and Lin (Lecturer in 1997, Senior Lecturer in 2002, Reader in 2005 and Professor in 2007) at Cardiff since 1997. The research has partly been driven by changes to planning laws concerning floodplains, increased flood insurance excesses, and increasing demands for improved water quality in rivers, estuaries and coastal basins.

The research covered in this case study commenced in 2000 with the integration of the DIVAST model with Research Centre's 1D river model (FASTER). Key developments included: fluid momentum conservation and solute (i.e pollutants and sediments) mass conservation, with particular emphasis on modelling dam break flows, and passing trans- and supercritical flows across 1D-2D boundaries. For example, the new model was applied to an embankment breach along the Thames, with CH2M HILL, through the Royal Academy Engineering's Industrial Secondment Scheme [3.1]. This refinement was extended to include lateral inflow/outflow boundaries, linking 1D-2D flows, where the flow passes from a 1D river onto the 2D floodplain (EPSRC GR/S76304).

In 2005 the model was refined from an implicit scheme to a novel and highly efficient shock capturing solver, giving highly accurate and efficient solutions for dam break and embankment breach flows. The model was subsequently developed to include a linked groundwater model within the solver [3.2]. This enabled flooding in urban environments to be modelled more accurately. Instead of using the traditional approach of blocking out cells covering buildings as solid cells; cells containing buildings are treated as highly impermeable and the groundwater equation for these cells is then solved. This innovative approach is more realistic in replicating the flooding of buildings on floodplains and is more accurate in predicting pollution levels in properties.

Since 2007, laboratory experiments have been undertaken on the incipient motion of scaled cars and model people in idealised rivers under flood conditions. Up-scaled prototype formulations have been developed for the onset of cars and people being moved by flood waters, both for buoyant and drowned vehicle conditions. These empirical equations have been developed for a range of vehicles and have been included in the numerical models for commercial flood risk hazard mapping [3.3],[3.4].

In collaboration with Aberystwyth University and the Environment Agency (EA), field and laboratory studies have been undertaken in the Severn and Ribble estuaries (2001-date). These studies focused on investigating the impact of turbidity on the decay (T_{90}) of enteric bacteria and the adsorption/desorption of bacteria with sediments as a function of turbidity levels in the estuary and in controlled conditions in the laboratory. New formulations have been developed and included in DIVAST for the relationship of the sink term in the solute transport equation. This involved the modelling of the dynamic decay process by relating T_{90} values for bacteria to turbidity levels, and adsorption/desorption of bacteria as a function of the level of suspended sediment in the water column [3.5].

Members of the HRC contributing to the research include: **Prof R A Falconer**, Director of the HRC, **Prof B Lin, Dr R Ahmadian** and **Dr B Bockelmann-Evans.**

3. References to the Research

3.1 **Lin B.,** Wicks J.M., **Falconer R.A.** and Adams K. (2006). Integrating 1-D and 2-D hydrodynamic models for flood simulation. *Proceedings of the Institution of Civil Engineers, Water Management,* Vol. 159 No. 1 pp. 19-25. (Awarded ICE Robert Alfred Carr Prize 2007). http://dx.doi.org/10.1680/wama.2006.159.1.19

3.2 Liang D., **Falconer R.A.** and **Lin B.** (2007). Coupling surface and subsurface flows in a depth averaged flood wave model. *Journal of Hydrology*, Vol. 337 No. 1-2 pp. 147-158. http://dx.doi.org/10.1016/j.jhydrol.2007.01.045

3.3 Xia J., **Falconer R.A., Lin B.** and Tan, G. (2011). Modelling of flash flood risk to people and property in urban areas. *Proceedings of the Institution of Civil Engineers, Water Management.* Vol. 164 No. 6 pp. 247-259. http://dx.doi.org/10.1680/wama.2011.164.6.267

3.4 Xia J. and **Falconer R.A.** (2013). People and vehicle stability in floods. *Innovation and Research Focus.* Issue No 95 pp.1. http://www.innovationresearchfocus.org.uk/

3.5 Yang L., **Lin B.** and **Falconer R.A. (**2008). Modelling enteric bacteria levels in coastal and estuarine waters. *Proceedings of the Institution of Civil Engineers, Engineering and Computational Mechanics.* Vol. 161 No. 4 pp. 179-186. http://dx.doi.org/10.1680/eacm.2008.161.4.179

Research Grants:

Falconer, R.A. and **Lin, B.,** *Flood Risk Management Research Consortium Phase 2,* EPSRC grant EP/F020511, 2008-11, held at Heriot-Watt, total value £7.3M. Cardiff value is £297k.

Falconer, R.A. and Xia, J., *The Royal Academy of Engineering Research Exchanges with China (Wuhan University),* Project 5502, 2012-13, £24k.

Falconer, R.A. and **Lin, B.,** *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, 2011-15, held at University of Sheffield, total value £1.76M. Cardiff value is £500k.

4. Details of the Impact

The impact of the research resulted from the sale and/or application of DIVAST, as illustrated for CH2M HILL (2000), Buro Happold (1999) and the Environment Agency North West (2000). The model's application by each of these organisations, and Professors Falconer and Lin's engagement with these organisations, has led to the following typical impacts in the REF period.

Economic – Buro Happold are currently using the model in the design of a major coastal waterway development project in Kuwait. Sabah Al Ahmad Sea City will eventually accommodate 100,000 people. The pioneering development is being constructed in five phases, two of which have

already been completed, and includes 180 km of shoreline, 2000 ha of water area and 81 million m^3 of water at high tide. The associated waterway network has been demonstrated to be viable as a direct consequence of Cardiff University's model. The waterway network is critical to the success and viability of the land-based development. DIVAST has been used for waterway alignment, waterway depth and width design, bridge, culverts and throttle design and flushing studies. The average price of serviced homes is £300k. Each phase typically has a base value of approximately £1.2B prior to development. [5.1]

Buro Happold's involvement in this project has developed and enhanced the company's international reputation in the coastal and marine engineering field. The CEO of Buro Happold (**Paul Westbury, FREng**) stated that: *"The research undertaken by Cardiff University and their on-going technical support to Buro Happold has played a key part in our success in Sabah Al Ahmad Sea City. This has resulted in really positive financial gain for the corporation (each of the five phases has an estimated base value of £1.2B prior to development). Moreover, the scale and success of the Sea City venture has been used to exemplify our specialist expertise and experience. It has consolidated our reputation and market positioning and led to successful bids for new, large scale contracts in Saudi Arabia, USA, China and Egypt (amounting to a combined value that exceeds £1M)."* [5.2], [5.3]

CH2M HILL (previously Halcrow) use the DIVAST suite to provide one of the principal engines for their 2D flood inundation models ISIS 2D and 2D-TVD (2009). ISIS 2D (and TVD) is marketed '*for use in surface water management plans and flood risk management studies*'. The ISIS suite enables flood risk and hazards to be predicted, the impacts on people, property and the environment to be assessed and mitigation options to be tested (notably, Defra have stated that the economic cost of flooding, £3.2B in 2007, could rise to £12B by 2080). CH2M HILL (Halcrow) is recognised as being one of the world's leading consultants in flood risk modelling. Over the last 60 years the company has operated in more than 120 countries and currently has more than 200 projects around the world connected to flood management. The models are widely used for flooding studies for UK and international clients; examples of users include the Environment Agency, Canals and Rivers Trust (formally British Waterways), Scottish Environment Protection Agency and Spain's Ministry for the Environment (CEDEX). **Richard Crowder**, Director at CH2M HILL, stated that '*the research undertaken by Cardiff University, and their ongoing technical relationship with CH2M HILL, has made a significant contribution to the capabilities of the ISIS software suite. This has been fundamental to us securing and delivering major flood risk projects in the UK and across the globe, including a long term contract with a major global insurance company to develop national scale flood risk models'*. [5.4]

The ISIS suite and the ISIS 2D engine can also be acquired by practitioners and researchers in both a fully featured paid for and reduced functionality free version from the CH2M HILL website (ISIS FREE). To-date over 12,000 users have downloaded the free version. CH2M HILL estimates that the models have been used to study the protection of over £10B assets to-date. [5.4],[5.5]

Environmental and Health Benefits - NASA Earth Observatory have stated that 2 billion people are likely to be vulnerable to flooding by 2050. The use of the models, individually or in combination, serves to help reduce these statistics. CH2M HILL, for example, have used the models (as part of ISIS 2D) to model over 700km of main river and major tributaries of the Siret River in Romania. This was to combat a series of flood occurrences in the last 40 years, including a major event in 2005 that resulted in fatalities, evacuations and damages to crops amounting to €500M. Another project supported the development of water management strategies in Argentina and Paraguay, The model simulated 90 days of a large flood event originating from the Pilcomayo River, which has one of the largest sediment loads in the world. Further examples include work for the Philippines Government, where the research is helping to map and manage potential flood risk scenarios for the entire country. [5.6]

Another use of the models concerns water quality. Illnesses derived from contact with contaminated water include gastroenteritis, respiratory tract, ear, eye and skin infections. Based on data regarding bather numbers (80 million swims per year), work for Defra infers that 1.3 million

cases of gastroenteritis each year could be associated with bathing in England and Wales. The EA North West used the linked model to establish the frequent cause of non-compliance of the bathing waters at Lytham St Annes. The results illustrated that non-compliance at the bathing beach was due to bacterial inputs from the river Ribble and combined sewer overflows from Preston Wastewater Treatment Works. Following the outcome of a Public Inquiry in 2008, where Professor Falconer was a key witness and the model was a key part of the evidence, United Utilities embarked on a £114M upgrade of the Preston works. This will bring '*significant environmental improvements to the Fylde coastal bathing waters (including Blackpool beaches) and designated shellfish beds located within the Ribble Estuary'*. [5.7]

Improving Industry Knowledge and Public Engagement –The research has been used to study the effects of the Severn Barrage and has significantly contributed to industrial knowledge and stimulated public engagement The findings are of national and international significance, particularly in terms of flood risk, water quality and power generation. They highlight that two-way generation could produce almost as much power as the traditionally favoured option of ebb-only generation, but with this operating approach considerably reducing the hydro-environmental concerns about siting a barrage in the Severn Estuary. Since 2008, Professor Falconer has delivered over 160 presentations on the Severn Barrage, flood modelling and water security to learned societies, such as The Royal Academy of Engineering, and given numerous media interviews to radio and TV channels - both in the UK and overseas. His research on the Severn Barrage also formed key evidence to the House of Commons Energy and Climate Change Committee in January 2013. [5.8],[5.9],[5.10]

5. Sources to Corroborate the Impact

5.1 http://www.burohappold.com/projects/project/sabah-al-ahmad-sea-city-71/ *Provides details of the Sea City Project.*

5.2 CEO of Buro Happold. *Confirms the use and impact of the research for Buro Happold*.

5.3 Director - Water Group at Buro Happold. *Confirms the use and impact of the research for Buro Happold.*

5.4 Director of CH2M HILL. *Confirms the use and impact of the research for CH2M HILL.*

5.5 http://www.halcrow.com/isis/documents/flyers/english/ISIS_FREE.pdf *Provides details of the free download available.*

5.6 http://www.halcrow.com/Our-projects/ *Provides details of the projects in which the model has been used.*

5.7 http://www.unitedutilities.com/preston/PrestonTunnels.aspx *Provides details of the United Utilities upgrade of the Preston Wastewater Treatment Works.*

5.8 List of over 160 presentations on the Severn Barrage and Flooding by Roger Falconer.

5.9 http://www.bbc.co.uk/iplayer/episode/b00b7rdy/Material_World_Severn_Barrage/ *Evidence of the inclusion of the research in the media.*

5.10 http://www.parliamentlive.tv/main/Player.aspx?meetingId=12443 *Evidence of Prof Falconer providing evidence to the House of Commons 'Energy and Climate Change Committee'.*