Institution: University of Leeds

Unit of Assessment: B10, Mathematical Sciences

Title of case study: Flood mitigation: from outreach demonstrator to a graphical cost-effectiveness diagnostic for policy makers

Period when the underpinning research was undertaken: 2015-present

Details of staff conducting the underpinning research from the submitting unit:

Name(s): (all Leeds-based)	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
	Prof	2013-present, UoL
Onno Bokhove	Prof	1990-present, UoL
Mark Kelmanson	Dr, EPSRC PDRA	2018-2020, UoL
Tom Kent	Dr, EPSRC network coordinator	2015-2018, UoL
Tiffany Hicks		

Period when the claimed impact occurred: 2015-present

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact

Researchers in the School of Mathematics have developed the "*Wetropolis*" flood-outreach demonstrator to enable visualisation of the so-called *return periods* of extreme rainfall and flooding events. *Wetropolis*, initially designed to be showcased to the general public [A,B], has accrued additional attention from flood professionals and academics [B] that has not only triggered the development of new quantitative tools for bridging science and engineering with environmental policy – deployed in analyses of flood-prevention in France [C–E] and Slovenia [F] – but has also seeded the development of educational material on water management [H(2)] .

Research developed in [1–3] led to a novel protocol, comprising theoretical and graphical mathematical tools for quantifying flood-mitigation approaches and their costing, that both quantifies the up-scaling of flood-mitigation measures and offers a consistency check on detailed calculations in engineering and consulting [2,5]. The protocol has been adopted by French civil engineers, collaborators of the Leeds researchers on [1,2], both within and beyond the EU network NAIAD (Nature Insurance Value: Assessment and Demonstration [E]). The accessible cost-effectiveness analysis on flood mitigation has additionally been well-received within the EU scientific and stakeholder community, and has also created a platform for engaging stakeholders in using the methodology [C–F].

A flood-evacuation plan [G(2)] based on a preliminary form of the research saved business equipment [G(1)] from damage during the 2015 Boxing Day floods on the Kirkstall Industrial Park in Leeds, UK. Real data from that evacuation plan used in the protocol improved the science underlying [2,5] and strengthened flood-warning predictions [G(2)].

2. Underpinning research

Return periods of extreme rainfall and flooding events are notoriously hard to explain to the general public. Bokhove and Dutch designer Wout Zweers developed the *Wetropolis* flood demonstrator in response to requests emerging, via [α,β], from the Environment Agency (EA), Pennine Prospects and JBA Trust. *Wetropolis* is based on a mathematically and numerically informed model design and was subsequently built as a transportable physical model [4]; it was showcased at many workshops and exhibitions to approximately 1000 people [A,B]. Though initially designed for public outreach, *Wetropolis* also drew the attention of UK flood professionals and academics.

The EA requested development of flood-science tools that are understandable to policy makers, many of whom are not conversant with the underlying mathematics: in this context, the partial differential equations of fluid mechanics. This led to the development [1–3] of quantification and communication tools for bridging science, engineering and policy.

Effective communication with stakeholders on flooding begins with the concept of (dynamical) *flood-excess volume* (FEV), the integrated excess discharge above the water level that quantifies the onset of flooding and associated flood damage. The representation of FEV was extended in a novel way and presented in [1,2] as a three-panel graphical display comprising the basic river-level measurements, the rating curve and the discharge hydrograph; uncertainty arising from observational estimation of the rating curve was also included. This visualisation formed a new basis for quantifying flood events and assessing potential and proposed flood-mitigation measures. The research [1,2] produced a cost-effectiveness tool that not only supports and encourages evidence-based decision-making by policy makers, such as city councils and the EA, but also informs the general public in an accessible way by conveying transparently the relative merits and costs of different sub-components (see below) of an integrated flood-alleviation policy; it is this inbuilt accessibility that gives the tool its reach [C–F].

Three papers have been published in international journals *River Research and Applications* (2019) [1], *Water* (2020) [2], and *Hydrology Earth Science Systems* [4], the last being an editorial-choice highlight article. All research was initiated within the EPSRC LWEC Network "Maths Foresees" [α] in a series of presentations by Bokhove at Environmental Modelling-in-Industry Study Groups and General Assemblies, and in discussions ensuing from [α] with the EA and JBA Trust. The methodology presented in [1–3] provides an accessible consistency check on flood-mitigation calculations and plans, resulting in a clear cost-effectiveness analysis that facilitates portfolio optimisation, either prior to a full-scale assessment or as an *a posteriori* executive and accessible summary or diagnostic of detailed engineering calculations [2,5]. The research quantifiably shows that up-scaling of pilot flood-mitigation approaches, including natural flood management, can be difficult, and even unrealistic [3,I]. It not only provides a novel consistency check on detailed calculations in engineering and consulting, but also offers a preliminary quantification of flood-mitigation approaches that can be readily understood by an interdisciplinary scientific and public community. Such a sanity check has been used to augment extensive computer simulations [2,5,C–E]. The research [1–3] has been well-received in the EU community [C–F] and has provided preliminary answers regarding the efficacy of natural flood management [1–3,5].

Personnel: Professors Bokhove and Kelmanson were permanent staff throughout the research. PDRA Dr Kent was funded by [α,β], and Dr Hicks was network coordinator for [α]. In addition to these Leeds-based personnel, Dutch designer W. Zweers (https://www.wowlab.nl/?page_id=381) was funded in an outreach project in [α].

3. **References to the research**

Preprint-version URLs augment those for journal publications where impact arose from work prior to final publication. Staff conducting the underpinning research from the submitting unit are highlighted in bold font. References best indicating the quality of the research are starred.

[1*] **Bokhove**, **O.**, **Kelmanson**, **M.**, **Kent, T.**, Piton, G., Tacnet, J.-M. (2019) Communicating nature-based flood-mitigation schemes using flood-excess volume. River Research and Applications **35**, 1402-1414. https://onlinelibrary.wiley.com/doi/full/10.1002/rra.3507 2018 Version: https://eartharxiv.org/87z6w/

[2*] **Bokhove, O.**, **Kelmanson, M.**, **Kent, T**., Piton, G., Tacnet J.-M. (2020) A cost-effectiveness protocol for flood-mitigation plans based on Leeds' Boxing Day 2015 floods. Water **1**, issue 2, 217-258. https://www.mdpi.com/2073-4441/12/3/652 2018 Version: https://eartharxiv.org/stc7r/

[3] **Bokhove, O.**, **Kelmanson, M.**, **Kent, T.** (2018) Using flood-excess volume in flood mitigation to show that upscaling beaver dams for protection against extreme floods proves unrealistic. Version July 2018: https://eartharxiv.org/w9evx/; this report fed directly into [2].

[4*] **Bokhove, O.**, **Hicks, T.**, Zweers W., **Kent, T.** (2020) Wetropolis extreme rainfall and flood demonstrator: from mathematical design to outreach and research. Hydrology and Earth System Sciences **24**(5), 2483-2503. https://doi.org/10.5194/hess-24-2483-2020 Published by European Geophysical Union as highlight article on 28-05-2020: https://www.egu.eu/news/highlight-articles/.

[5] **Bokhove, O.**, **Kelmanson, M.**, **Kent, T.** (2020) A new tool for communicating cost-effectiveness of flood-mitigation schemes. Evidence summary of [1–4,A–G,I] to the Environment, Food and Rural Affairs Committee inquiry into flooding: https://committees.parliament.uk/work/107/flooding
Evidence: https://committees.parliament.uk/writtenevidence/9641/pdf/

Grants and awards

[α] **Bokhove, O.** (PI) and Pender, G. (Co-I, Heriot-Watt). Maths Foresees: EPSRC Living with Environment Change Network (EP/M008525/1, 2015-2018). https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/M008525/1 and http://www1.maths.leeds.ac.uk/mathsforesees/

[β] Dance, S.L. (PI, Reading University) and **Bokhove, O**. (Co-I). Data Assimilation for the Resilient City. EPSRC Fellowship (EP/P002331/1, 2016-2021). https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/P002331/1

4. Details of the impact (indicative maximum 750)

(a) **Public and consulting outreach (England and Scotland):** The *Wetropolis* flood demonstrator has been showcased to circa 1000 members of the public in the UK [A,B]. Wetropolis was first showcased as outreach at the second general assembly of the Maths Foresees network, 5-7 September 2016, Edinburgh. As part of this outreach project and such showcasings, Bokhove has given several public lectures [B], including at the Science of Floods workshop in Hebden Bridge (24-05-2016), Churchtown flood-action group workshop (28-01-2017), Flood & Coast 2019 conference (bespoke conference mainly for and by non-academic flood professionals), Telford, UK; and during a nine-day Mathematics of Planet Earth (MPE) Science exhibition at Imperial College (15-23 February 2020) with "*hundreds of visitors per day"* [A(1)]. "*The French counterpart at Centre de Science, Orleans* [showing several other exhibits] *would like to make the exhibit into a permanent feature of the MPE exhibitions and they are proposing to produce a copy of Wetropolis to be presented around the world*" [A(1)] (although it concerns a future action, the previous quote is included to corroborate a positive response). Visitors to the exhibition left positive feedback , e.g. *"Very nice to see numbers in action!"* [A(1)]; *"What a wonderful and insightful exhibition"* (an MP) [A(1)]. A letter from Hydrotec Consultants [A(2)] Ltd states: "*During the development of Wetropolis II, Hydrotec contributed in-kind effort to augment that put in by the University of Leeds. ... The release of Wetropolis II has also promoted the skills and versatility of Hydrotec within the wider water-treatment industry*".

(b) **Educational innovation (Netherlands):** *Wetropolis* made possible the Efro EU project "*Wetropolis*: interactive, tangible models for education and water management" in The Netherlands [H], a project involving various SMEs. The project has developed educational tools that are either inspired by, or directly based on, Wetropolis [4,Appendix of H(1)]: "*Inspired by the Wetropolis-Leeds mathematical and physical models, a project was defined to use the Wetropolis-approach for water-management issues in the Netherlands. A grant was provided by EU-EFRO (https://www.op-oost.eu/Overzicht-beschikte-projecten) for the WetropolisRD project, involving academic partners and several SME's. Based on the original Wetropolis demonstrator, new ways were investigated to produce scale models for local or foreign water management issues and introduce this approach in education and outreach-projects for public understanding. ... The methods to produce these models have been tested in the classroom (in the academic year 2019-2020). The methods will be further developed to certified lessons for NLT.*" In addition [H, translated from the original Dutch]: "*First, the project has inspired the building of bespoke physical models [cf. our Wetropolis model] by a team of pupils/students in the education that the Pre-U [program] of the University of Twente undertakes in collaboration with four high schools in the Eastern part of The Netherlands. The approach has proven successful and has been presented to a national conference with 180 schools which offer the optional module Nature, Life and Technology (NLT).*" See also publication in Dutch journal on secondary education [H(2)].

(c) **Influencing policy (France):** Following the extreme and fatal 2015 flooding of the River Brague, Antibes, France [1], French civil engineers (at the University of Grenoble, France) have

independently used and continue to use [C] the new diagnostic tool [1,2] discussed in Section 2 together with stakeholders [D] in a flood-mitigation-planning work package [E] for the River Bragues. The work package is part of the EU network NAIAD (Nature Insurance Value: Assessment and Demonstration) [E]. The French civil engineers developed the methodology [1] for the River Bragues case and independently influenced flood-planning policy [D] for the municipality [text removed for publication], France.

The French civil engineers are co-authors of [1,2] and providers of corroboration [C(1)], in which latter role they act as *"impact intermediaries"* for this component of the case study: they write in [C(1)], dated 30-08-2019: "*Prof. Bokhove and his colleagues Prof. Mark Kelmanson and Dr. Thomas Kent shared with us their idea of the decision aid framework they developed with the Flood Excess Volume analysis. We implemented it on a case study in the south of France (Brague River at Antibes) within the H2020 EU granted project NAIAD* (http://naiad2020.eu/)" and "*The method results were presented during several public meeting* [sic]*, e.g., on Dec. 18th, 2018 to a panel of stakeholders and citizens of the catchment, Feb. 12th, 2019 to the Water Agency (AE-RMC) and on Mar. 28th, 2019 to the regional authority in charge of risk and environment management (DDTM 06). Every time, the approach was well received and all stakeholders, from various background* [sic]*, agree that it helps understanding the magnitude of the flood and the efficacy of the strategy proposed. All these stakeholders agreed that the framework provides very clear and directly applicable elements for helping decision and raising citizen awareness on mitigation measure efficacy. It is definitely a useful tool*".

(d) **Influencing policy (Slovenia):** The tool developed in [1,2] is also being used by French and Italian civil engineers in collaboration with Slovenian stakeholders regarding flooding in Ljubljana of the Glinščica river, Slovenia [F(1)]. The Slovenian stakeholder is the NGO Instituto Revivo (www.ozivimo.si) together with City Municipality of Ljubljana*: "… After the stakeholder workshop, an effort was made to collect feedback from the stakeholders, including their appreciation of the FEV model outputs. While the ethical rules of the NAIAD project prevent us from sharing individual responses, they confirm that our target stakeholders belonging to the City Municipality of Ljubljana not only trust and understand the results, but also plan to use them in their future activities*" [F(1)]; the NGO received assistance from Italy: "*The FEV-based methodology described e.g. by Bokhove et al. (2019, River Research and Applications) has been applied in the Glinščica for a twofold reason: … (ii) to facilitate stakeholder participation to the co-design process*" and "The adopted approach definitely helped, according to the feedbacks provided by the participant, improving the quality of the whole decision-making process" [F(2)].

(e) **Local flood-evacuation planning (West Yorkshire, England).** Nascent research, ultimately appearing in [2] and subsequently reported in [5], gave an estimate (embedded in river-level data and in-situ observations) of the flood threshold height that was used to initiate a bespoke flood-action plan [G(2)] for the business CrossFit Leeds in Kirkstall, Leeds. The nascent plan was effectively employed during the 2015 Boxing Day Flood of the River Aire and saved CrossFit more than GBP 20,000 [G(1)], since they were able to act in good time on warnings provided by Bokhove: CrossFit "*saved over 20,000 pounds worth of gym equipment (including 10 Concept2 rowing machines each worth more than 1,000 pounds). That successful evacuation (as well as the fast clean-up effort by the entire membership) enabled CrossFit Leeds to open relatively soon in January 2016, thus saving the business from a significant loss of income*" [G(1)].

The plan was subsequently formalised on 29-12-2015 [G(2)], in which form it was used on 09-02-2020 by CrossFit during Storm Ciara, although in this case the evacuation of CrossFit on 09-02-2020 transpired not to be necessary, since the water stopped approximately 0.1m below the floor level of the premises. CrossFit reported that they shared the plan and timings with nearby businesses (some of which were flooded) who found these useful during Storm Ciara [G(1)].

(f) **Improving public understanding of science (UK):** J. Rand has cited reference [3], which fed into [2], in a comment in New Scientist [I] regarding UK Government misconceptions that beaver dams can provide serious flood protection: "*Onno Bokhove and colleagues calculated that about 8500 beaver colonies would have been needed along parts of the River Aire in West Yorkshire, UK, to have coped with the Boxing Day floods of 2015*" [I] and "*Beavers are lovely in themselves and we should celebrate their reintroduction, but let's not get carried away and encourage government to think they are a cheap flood prevention solution*" [I].

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

[A] (1) Corroborating letter from professor at Imperial College, London on the showcasing of Wetropolis at Imperial College, from CDT Mathematics of Planet Earth (estimated "*100s of visitors every day*", 22-05-2020).
(2) Letter from Hydrotec Consultants Ltd on Wetropolis' construction (06-01-2021).

[B] (1) Showcasing to academics and flood professionals at the 2017 Environmental modelling in Industry, study group at Isaac Newton Institute Newton Gateway to Mathematics in Cambridge (link to live report including Wetropolis):
https://gateway.newton.ac.uk/event/tgmw41/live-report
(2) Churchtown flood-action group conference (28-01-2017):
https://www.thewestmorlandgazette.co.uk/news/14975893.list-of-post-floods-work-to-be-carried-out-in-cumbria-this-week/

[C] (1) Letter of support (16-03-2021) from two researchers at Irstea (now part of Inrae) – Centre de Grenoble.
(2) Public NAIAD report dated 02.06.2020 [Title translated to English: Risk of flooding in the Brague basin (Alpes-Maritimes, France): re-analysis of the events of October 2015 using the FEV method]. Downloadable at https://hal.archives-ouvertes.fr/hal-02866215/document

[D] Statement (05-06-2020, in French) from French stakeholder municipality [text removed for publication], France, regarding use of tool in River Brague basin; the "*note synthétisant*" therein refers to the report at [C(2)].

[E] Report within EU NAIAD network work package WP6, Deliverable WP6.2 (pp. 221-271) by researchers at Irstea, into which the Leeds research fed, publicly available at
at http://naiad2020.eu/wp-content/uploads/2019/02/D6.2_REV_FINAL.pdf

[F] (1) Corroboration letter from the Scientific Director of Instituto Revivo, Ljubljana, Slovenia (05-04-2020).
(2) The FEV diagnostic for the Glinščica river has been developed in collaboration at IRSA-CNR (Bari, Italy; 01-04-2020). Corroboration letter from researcher at IRSA-CNR.

[G] (1) Corroboration letter from owner of CrossFit Leeds concerning flood events in 2015 and 2020 (03-03-2021).
(2) Formalised flood-evacuation plan for CrossFit Leeds (29-12-2015), authored by Onno Bokhove in discussion with the owner of CrossFit Leeds.

[H] (1) Letter (in Dutch) from EU project leader at Saxion University of Applied Sciences, with appendix in English (28-05-2020). The project involves several SMEs (www.wetropolis.nl).
(2) supplementary reference confirming use of Wetropolis in secondary education: Wietsma, Zweers 2020: Wetropolis 3D modellen voor waterbeheer bouwen. NVOX **10**, 51-53. [Building Wetropolis 3D models for water management]. Article in Dutch journal (publication by Dutch professional organisation on secondary education in natural sciences):
https://www.nvon.nl/nvox/wetropolis---3d-modellen-voor-waterbeheer-bouwen

[I] Evidence regarding beavers in letter from J. Rand to New Scientist dated 16-01-2019.
https://www.newscientist.com/letter/mg24132131-000-youd-need-wall-to-wall-beavers-to-dam-floods/