A new tool for communicating cost-effectiveness of flood-mitigation schemes: DEFRA inquiry submission and subsequent discussion with Leeds City Council

Onno Bokhove[1], Mark Kelmanson[1], Tom Kent[1], Guillaume Piton[2] and Jean-Marc Tacnet[2]
[1] School of Mathematics and Leeds Institute for Fluid Dynamics (LIFD), University of Leeds, Leeds LS2 9JT, W. Yorks., UK
[2] Univ. Grenoble Alpes, INRAE, UR ETGR, Centre de Grenoble, F-38402, Saint-Martin-d'Hères, France

October 29th 2020

Resumé This document is an amalgamative overview of materials emerging from both work on a new flood-mitigation protocol conducted by the authors since 2017, and recent discussion thereon with its targeted beneficiaries at Leeds City Council.

- Part 1 of the following comprises the verbatim text of a September 2020 submission by the authors to an ongoing DEFRA committee inquiry into flooding.
- Part 2 is a discussion (October 2020) of Part 1 in the form of the authors' point-by-point responses to verbatim comments by the senior flooding engineer at Leeds City Council.
- Part 3 is a graphical overview of the authors' protocol that augments Figure 1 of Part 1 in both a quantified and visually striking way.

Part 1 : Environment, Food and Rural Affairs Committee inquiry into flooding

Submission: A new tool for communicating cost-effectiveness of flood-mitigation schemes

Summary:

- The "Wetropolis" flood-outreach demonstrator has been developed at Leeds to enable live visualisation of so-called return periods of extreme rainfall and flooding events to the general public.
- A team of Leeds mathematicians and French civil engineers has developed a novel and innovative way of visualising and analysing complex flood-protection schemes.
- This protocol, or tool, has been designed with the express intention of empowering decision-makers and flood action groups, as well as the general public, to make quantified judgements on the cost-effectiveness of flood-mitigation plans in order to facilitate enhanced evidence-based decision-making. The tool enables rapid *a priori*, as well as thorough *a posteriori*, comparisons to be made of various flood-mitigation options and scenarios.
- To date, the tool has highlighted that, in contrast to media promulgation, the effectiveness of Natural Flood Management (NFM) in the mitigation of medium- to large-size floods is small, if not minute. For example, at least 8500 beaver colonies — an unrealistic and unattainable upscaling — would be required to mitigate the notorious Boxing Day 2015 floods in Leeds.
- The tool is, however, objective, and so could equally highlight that for certain floods – i.e. sufficiently small and localized, with a "flood-excess volume" (see section 1.2 below for definition) of less than ~10,000 cubic metres, one beaver colony could potentially mitigate ~20% of the damage, with the remaining ~80% needing to be absorbed by other flood-mitigation measures.
- Hence, referring to the ToR, the new tool demonstrably addresses how "*communities can be involved most effectively*" [**ToR#4]** in flood mitigation, how "*increasing focus on natural flood management measures*" [**ToR#5]** has to be put in an evidence-based context of being predominantly relevant for the mitigation of small-scale floods, and how "*lessons can be learned from the recent winter floods*" [**ToR#7]**. We subsequently refer in bold, with accompanying reasons, to where **[ToR#3, ToR#4, ToR#5, ToR#7]** are relevant in the main text.

Researchers involved:

- The work is a collaboration between applied mathematicians Professor Onno Bokhove, Professor Mark Kelmanson and Dr Tom Kent from the School of Mathematics at the University of Leeds, UK; and, civil engineers Dr Guillaume Piton and Dr Jean-Marc Tacnet from Université Grenoble Alpes, France.

Reason for submission:

- Return periods of extreme rainfall and flooding events are notoriously difficult to explain to the general public. To circumvent this difficulty, the Wetropolis flood demonstrator was developed by Bokhove and Dutch designer Wout Zweers in response to requests – made by the Environment Agency (EA), Pennine Prospects and JBA Trust – to visualize return periods in a live demonstration **[ToR#4, ToR#7]**.
- The reason for making this submission is to allow the science underlying flood mitigation to become better understood by (international) citizens and the people involved in policy making **[ToR#4]**.
- Moreover, stakeholder involvement at several implementation phases of flood-mitigation plans is becoming increasingly common, but the technical complexity of some strategies, often involving multiple and disparate measures, hampers enlightened and, more importantly, quantifiable, decision-making **[ToR#4, ToR#5]**.

- There is therefore a need for educational tools and sanity checks, such as the one presented here, that facilitate understanding and communication of the efficacy of complex flood-mitigation strategies, additionally because "*these* [normative] *debates are* [often] *not held in an open and inclusive way, incorporating the views of all stakeholders*" (*q.v.* the introduction in reference [2] below) **[ToR#4, ToR#5]**.
- Finally, the tool has recently been applied in France and Slovenia, where it has been well-received by the stakeholders involved **[ToR#4, ToR#5]**.

THE NEW PROTOCOL

1. Contextualisation of flood data

1.1. *Introduction:*
The *Wetropolis Flood Demonstrator* is based on a mathematically and numerically informed model design and has subsequently been built as a transportable physical model [1]. It has been showcased at numerous workshops and exhibitions to approximately 1000 people in 2016-2020. Though initially designed for public outreach, Wetropolis drew the attention of UK flood professionals and academics. By demonstrating what a return period is, Wetropolis pertains to **[ToR#4, ToR#7]**. It subsequently triggered the development of a new quantitative tool, which has been deployed in analyses of flood-prevention in France and Slovenia, to date, for bridging science and engineering with environmental policy **[ToR#4, ToR#5]**.

This new tool for communicating the integrated magnitude and cost-effectiveness of flood-mitigation schemes has been developed by an international team of researchers comprising UK applied mathematicians and French civil engineers. The new tool deliberately eschews equations and scientific jargon and instead uses a graphical display that shows, as a hypothetical square lake 2 metres deep, the amount of water that needs to be contained in a river valley to stop a river from flooding. The graphic is overlaid with the various options necessary to hold back or to capture the floodwaters, and, more crucially for the purposes of strategic quantification, how much each option will cost. The tool is designed to help both the public and policymakers grasp the headline options and trade-offs inherent in flood-mitigation schemes, and it has already led to better decision-making regarding flood defences in France and Slovenia, particularly where a number of alternatives are being considered. The work grew from a challenge posed by a representative of the Environment Agency (EA) in the UK, who asserted that mathematicians generally explain things in terms of specialist equations and, instead, wanted something that was more accessible: a way of communicating complex ideas clearly and simply, in order to allow the science underlying flood mitigation to be understandable to both citizens and the people involved in policy making alike, **thereby addressing [ToR#4, ToR#5]**.

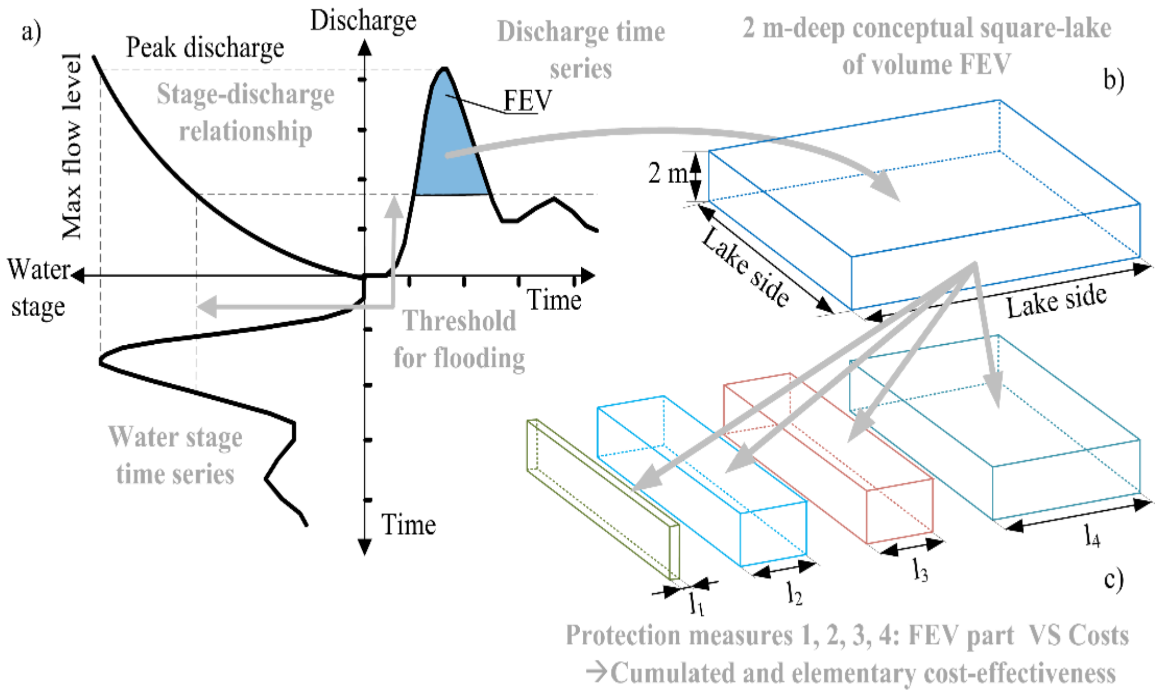

Fig. 1: Schematic diagram of the combined conceptual flood-excess volume (FEV) and cost-effectiveness approach. (a) Three-panel graph highlighting FEV: (bottom-left) view of river-level time series around a flood event; (top-left) stage-discharge relationship arising from (top-right) discharge data, in which FEV is the blue-coloured "area" between the discharge curve, displayed vertically as function of time horizontally, and a chosen threshold discharge over the duration of the floods, involving in-situ temporal river levels as function of time. (b) FEV square-lake representation as a 2-metre-deep square lake, with side-length "Lake side" being the square root of half the FEV (i.e. FEV divided by 2 metres), to facilitate visualisation of FEV "size". (c) FEV-effectiveness assessment computed for each measure, here four, as an equivalent FEV fraction, represented as side lengths l_1, l_2, l_3 and l_4 of the square lake.

1.2 *Background:* The research team revisited a concept at the heart of flood analysis: known as *"flood-excess volume"* (FEV), it is the amount of water in a river system that cannot be contained by existing flood defences. Expressed alternatively, FEV is the amount of water that caused the flooding, expressed as so many thousands or millions of cubic metres of water. Consequently, when this FEV is nullified by one or a variety of flood-mitigation measures, there will be no flood damage in a future flood of similar FEV and/or river levels. However, for most people, including the team of researchers, expressions involving thousands or millions of cubic metres elude meaningful interpretation and/or visualisation. So, instead, FEV is re-expressed in terms of a square lake with a (human-scale) depth of 2 metres. The approach is described in the team's two recent peer-reviewed international publications [2,3], both of which have been deliberately written in a pedagogical style aimed at a general-yet-interested audience. Fig. 1 depicts a schematic diagram of the methodology underlying the philosophy used in [2,3], thereby highlighting that FEV pertains to **[ToR#4]** via the education of citizens, cf. the use of hydrographs in Slow-the-Flow.

1.3 *Exemplification:* To illustrate the idea, data have been analysed from the floods on Boxing Day 2015, when the River Aire burst its banks in Leeds and caused extensive damage to homes and businesses; damage estimated at around half a billion pounds. Around 9.34 million cubic metres of water flooded from the River Aire on Boxing Day 2015 into the Kirkstall/Armley area of Leeds. Such a volume of flood water translates into a hypothetical square lake of depth 2 metres, with sides of length 2161 metres. By comparison, the upper River Aire is about 50 miles long, with a valley width that varies along its path roughly between 200 and 600 metres. To have prevented the Boxing Day 2015 flood, one would have had to somewhere deal with that volume of water. It is not inconceivable that, along the course of the river, additional water storage could have been accommodated, either by increasing the size of flood plains or by removing obstructions in the river, widening the river channel in places (also called giving-room-to-the-river or GRR) or by building higher flood walls. More likely, one would have needed to combine some or all of these measures. Visualising flood mitigation in this new way makes it easier for people to understand not only the interventions that are possible – i.e. their size and the impact they are likely to have – but also the costs associated with each such constituent flood-mitigation measure. This example relates to **[ToR#4, ToR#5]** because it not only advises the public on flood-mitigation measures but also, in particular, on Natural Flood Management (NFM).

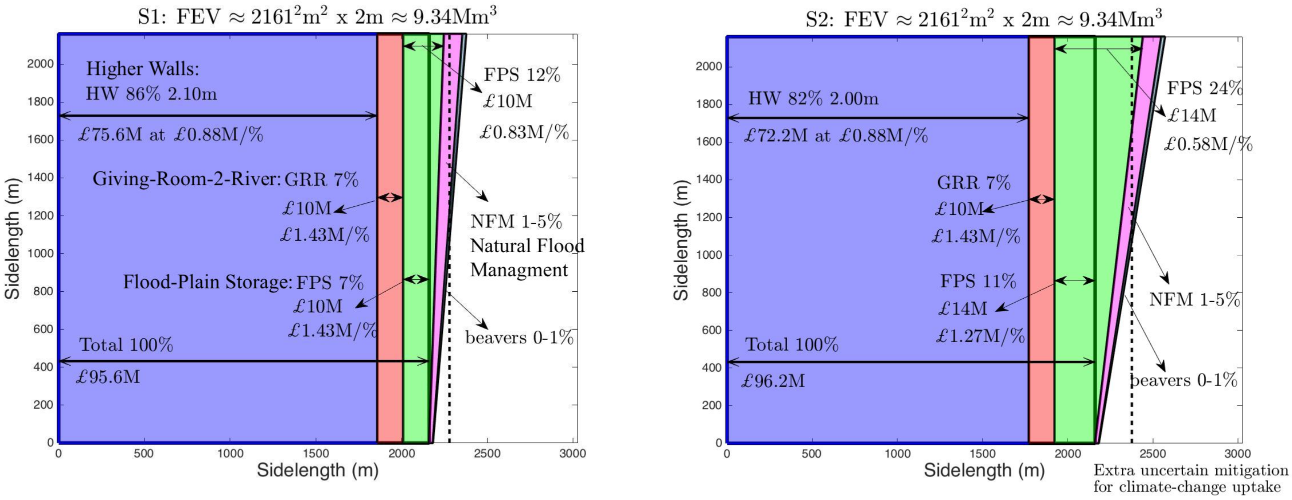

Fig. 2: Two scenarios S1 and S2 in the hypothetical Leeds flood-alleviation scheme. The flood-excess volume FEV of 9.34 million cubic metres of the Leeds' Boxing Day 2015 floods (the FEV that caused the flood damage) is represented as a square lake (viewed from above) of depth 2 metres with sides of length 2161 metres (about 1.25 miles). Each coloured segment represents the portion of the hypothetical square lake absorbed by a specific mitigation measure. Cost and cost per percentage covered per mitigation measure (i.e. by each segment) are displayed (above and below) the double-sided arrow pertaining to that segment, as well as the total or overall costs of that scenario. Additional-yet-uncertain mitigation is offered in part by flood-plain storage (FPS, green), or via Natural Flood Management (NFM, pink) and 85 beaver colonies (the small silver sliver). For a large flood such as that of Boxing Day 2015, the contribution of NFM and 85 beaver colonies is small-to-minute, as well as uncertain, leading to the two thin pink and silver slivers, which are small in area relative to the areas of other measures such as higher walls (HW, dark purple) and river-bed widening (GRR, red). Scenario S1 concerns a case with flood-plain storage in Calverley and scenario S2 one with larger flood-plain storage in Rodley, both areas being within 7 miles of Leeds. (Images adapted from [2], in which also three other scenarios are introduced and compared.)

2. Scoping and planning

2.1 *Cost-effectiveness visualisation:* The researchers have used their novel graphical approach to analyse and to communicate a hypothetical scheme for increasing the flood defences in the Kirkstall/Armley area of Leeds, upstream of Leeds' City (railway) Station, to cope with not only a major flood that would be expected once in 100 years but also a once-in-200-year flood. They looked at several mitigation scenarios, their costs and their impact on river dynamics, a sub-topic of the scientific discipline of *"fluid dynamics"*, in which the University of Leeds is a world leader. The accompanying graphics in Fig. 2 show two such hypothetical scenarios. With colour-coded overlays, it shows how higher flood-defence walls (denoted by HW), more flood-plain storage (denoted by FPS) and river-widening (denoted by GRR) could provide the additional drainage necessary to avert a repeat of the scale of flooding seen in 2015. Another graphical analysis in Fig. 3, of the River Calder Boxing Day 2015 flood in Mytholmroyd, highlights, in terms of sloping lines, bounds on the inherent uncertainty in flood-mitigation measures: the use of water reservoirs in the upper catchment to hold rain water by drawing down reservoir levels is seen to be potentially very effective relative to the smaller contributions of tree planting and leaky dams, even though tree planting and the number of leaky dams have been upscaled to a deliberately exaggerated level that greatly exceeds that in existing plans. Several such analyses, investigated in [2,3] and presented by the team at various national and international meetings, reveal the limited impact of Natural Flood Management (denoted by NFM). That is, in stark contrast to what many people in the UK are led to believe, the planting of trees or the introduction of "realistically numerous" beaver colonies to build dams can at best have limited impact on the mitigation of bigger floods. In summary, the visualisation approach directly pertains to **[ToR#4]** through both its involvement of the public and the support it offers to decision-making.

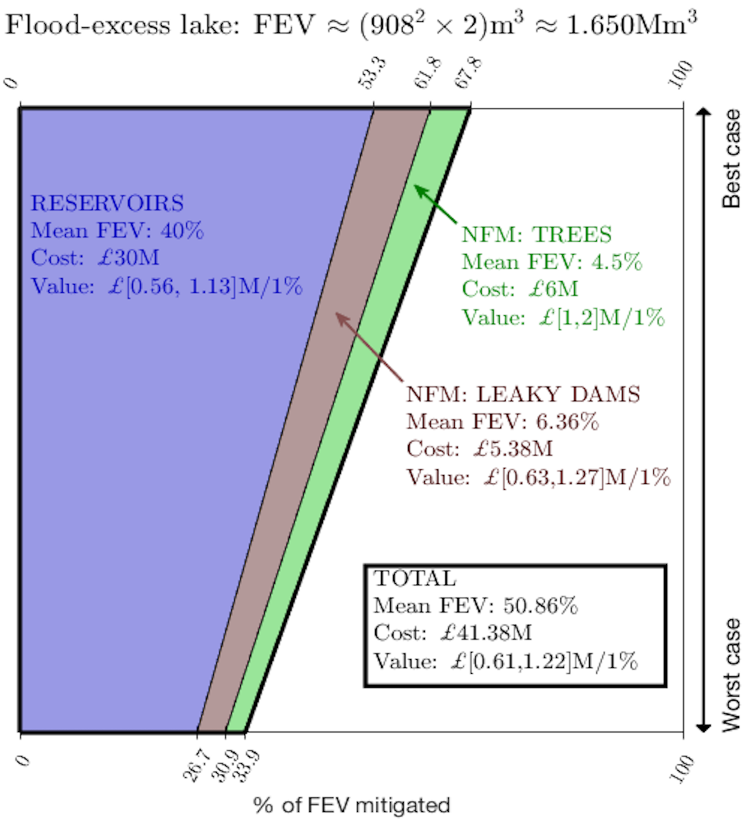

Fig. 3: Graphical overview of FEV fraction captured by three flood-mitigation measures and associated costs for the River Calder at Mytholmroyd. The FEV here is 1.65 million cubic metres and is represented as a 2-metre-deep square lake of side-length 908m. Overall flood-mitigation ranges from 33.90% to 67.81% at a cost of £41.38 million. The mean contribution of each of the constituent flood-mitigation measures is represented by corresponding quadrilateral areas, indicated by "reservoirs" (purple), "NFM: trees" (brown) and "NFM: leaky dams" (green); together, these partition the overall square-lake area with the same FEV capacity requiring mitigation. Sloping lines reflect the sliding scale between quoted ranges accruing from storage-capacity uncertainty. The remaining (white) area should be covered by other measures, such as in-situ higher walls or river-bed widening (i.e. GRR) in Mytholmroyd. (Image reproduced from [3].)

2.2 *Protocol-application credentials:* The newly developed tool can be and has already been used in two ways. Given in-situ flood data, it can provide a quick *a priori* investigation to explore and to propose various flood-mitigation scenarios: in this vein, a non-governmental organisation in Slovenia [4] has used the tool to explore the effectiveness of Nature Based Solutions in flood mitigation. Alternatively, it can be used *a posteriori* as an executive summary of complicated, costly and extensive computer simulations undertaken by engineers. In the latter case, the new tool offers a relatively cheap and easy-to-implement protocol and sanity check of such technical calculations for not only decision-makers and citizens but also for the technical experts involved. The French civil engineers in the team that designed the tool have used it to communicate complicated hydrodynamic simulations for the River Brague in South-East France, following devastating floods there in 2015 and, more recently, in 2019.

Additionally, recent 2019-2020 winter floods in both the UK and Indonesia have been and continue to be analysed in undergraduate projects that have deployed our approach. This analysis has already highlighted that essential river-discharge data are sometimes missing from data currently gathered by the EA, and that this lack of data partly obstructs the construction of flood-mitigation plans requiring FEV. That is, through the use of our protocol, an important novel conclusion – that current data gathering may be suboptimal – has been revealed. In summary, our protocol directly pertains to **[ToR#4]**, involving the public and support decision-making.

2.3 *Bespoke flood-evacuation warning/plan*: During the 2015 Boxing Day floods in Leeds, an *ad hoc* flood evacuation of local business *Xfit The Forge* (*XTF*) was triggered by an author (OB) of [2]. This was based on the levels and their rate of increase (as recorded on the nearby Armley river gauge) of the River Aire during the flood, as well as local knowledge of critical flood levels for *XTF*, the latter being acquired during observations of a minor-flood peak in mid December 2015. Over £5000 of gym equipment was saved and *XTF* could consequently re-open quickly, as one of the first on the Kirkstall business estate. This *ad hoc* plan was subsequently formalized by OB in [5], and (re-)used during Storm Ciara in February 2020 (after OB had issued a warning on the day) by *XTF* for its evacuation of gym equipment; the plan had moreover been shared by the owner of *XTF* with nearby businesses. While *XTF* escaped flooding with only 10cm to spare, nearby premises were indeed flooded by Storm Ciara. The essence of the bespoke plan is that it uses local (photographic) evidence to augment, with timings regarding evacuation, warnings provided by the EA. This hands-on experience triggered work that led to papers [2,3] and provided first-hand evidence factually used in [2]. Although the use of this particular extended flood-evacuation plan from February 2020 pertains to **[ToR#7]**, it is important to stress that is not only readily adapted to other locations, but also can be automated using modern Data Science methodology, thereby specifically addressing quantification of the "*level of investment … required*" in **[ToR#3]** and being a proactive contributor to the "*communities most effectively … involved …*" in **[ToR#4]**.

2.4 *Contribution to future UK policy:* Finally, though the UK Government will over the six years to 2021 have spent £2.6 billion [6] on flood schemes in England, further investment is expected. Specifically, it aims to increase such spending in the manner recently announced by the UK Environment Secretary [7]. Thus the new approach could well prove useful in its intended role of offering a protocol for comparing and choosing between flood-mitigation scenarios in a quantifiable, evidence-based and visual manner, thereby offering a better chance of the available options and costs being understood and accepted by a wide audience including the general public, stakeholders and planners. In summary, our education demonstrator Wetropolis, our decision-making tool and our extended flood-evacuation plan pertain to **[ToR#3, ToR#4, ToR#5, ToR#7]**.

References

[1] Wetropolis Flood Demonstrator, GitHub design site: https://github.com/obokhove/wetropolis20162020

[2] Bokhove, O., Kelmanson, M.A., Kent. T., Piton, G. and Tacnet, J.-M., A cost-effectiveness protocol for flood-mitigation plans based on Leeds' Boxing Day 2015 floods, *Water* **12(3)**, 652-682, 2020. https://www.mdpi.com/2073-4441/12/3/652

[3] Bokhove, O., Kelmanson, M.A., Kent. T., Piton, G. and Tacnet, J.-M., Communicating (nature-based) flood-mitigation schemes using flood-excess volume, *River Res. Appl.* **35(9)**, 1402-1414, 2019. https://onlinelibrary.wiley.com/doi/full/10.1002/rra.3507

[4] Slovenian Instituto Revivo, http://www.ozivimo.si/en/

[5] 2015 Flood-evacuation plan for *Xfit The Forge*:
https://github.com/obokhove/wetropolis20162020/blob/master/BokhoveXfitPlan.pdf
Facebook-Messenger correspondence, comments/photographs, during Storm Ciara:
https://bardvantwenthe.wordpress.com/2020/02/29/kirkstall-flood-evacuation-during-storm-ciara/

[6] https://www.gov.uk/government/news/government-pledges-62m-flood-funding-for-communities-in-england

[7] Quote by George Eustice, UK Environment Secretary on page 3 of transcript:
http://news.bbc.co.uk/1/shared/bsp/hi/pdfs/23022001.pdf of Andrew Marr Show, BBC1, 23/02/2020.

Part 2: Discussion on "*A new tool for communicating cost-effectiveness of flood-mitigation schemes*"

Background

The FEV cost-effectiveness tool revealed inconsistencies in LFAS2 [1] communicated to LCC in 2017-18. It is noted that targeted LCC and EA recipients of early (pre-publication) drafts of journal papers [2,3] and the tool/protocol [4] elicited no substantive feedback throughout 2017-20. Therefore, the following discussion between the authors of [1] (**[C]**omments in black) and [2,3,4] (**[R]**responses in blue) provides the first substantive and interesting exchange on the matter.

Discussion

- **[C1]** In summary, I would probably kindly discourage the use of FEV as I think it misses the point a little. However, the plots shown are useful in terms of build up of measures and how they build in a modular way to create a solution – I just think this needs to be in terms of flow reduction towards a threshold of flooding (in flow) rather than volume/FEV. Then I think this would be a useful way of communicating what each measure does in terms of necessary flood risk prevention v how much it will cost.

  [R1] Since the (cross-sectional) "*flow*" mentioned in **[C1]** is expressed in m^3/s, temporal integration above a flow or water-level *threshold* (related via a rating curve) gives one the FEV. That is, FEV is the temporal integration of a dynamic quantity, so FEV is hereafter referred to as *dFEV* to highlight unequivocally its dynamic origin. Note too that all flood-mitigation measures used in the (NB virtual) square-lake representations in [2,3], for various international scenarios and rivers, are similarly based on temporal integrations of dynamic flow.

- **[C2]** FEV (as you've presented) is a very useful tool for describing the size of a flood management problems, specifically for a particular event.

  [R2] In the road-map in [2], specifically advocated is the use of ensemble predictions leading to ensemble dFEVs and ensemble flood-mitigation scenarios, i.e. concerning an ensemble of flood events. However, in order to introduce/exemplify the methodology, focus was deliberately placed on particular worst-case events.

- **[C3]** However, there is a real risk here that using this as an example means that interested parties focus on storage based solutions, rather than the whole suite of potential flood management measures that we have at our disposal and their physical impact – for example improving conveyance (which reduces the FEV for a specific event, but doesn't store it, or NFM infiltration improvements, raised walls etc. all of which have a similar impact, but not by storing water, just by reducing the volume that exceeds the defence or channel capacity and therefore reducing the FEV.

  [R3] The "*focus on storage-based solutions*" mentioned in **[C3]** is manifestly not advocated in [2,3], in which the square-lake graphs for various scenarios and rivers (with different colours for each flood-mitigation measure) clearly show that, in all but one case, a handful of flood-mitigation measures (some of which are mentioned in **[C3]**) are considered. These include higher walls, giving room to the river (GRR), dynamic flood-plain storage (using controllable weirs), NFM (including e.g. leaky dams, trees, beavers), dynamic draw-down of reservoirs. That is, explicit and deliberate consideration is given to the *"whole suite of potential flood management measures"* mentioned in **[C3]** , including GRR for *"improving conveyance"* (see https://www.preventionweb.net/publications/view/59399). In one case higher walls in isolation are considered, but only because this ties in with the explicit highlighting in [2] of the observation that LFAS2 is based on ~85% dFEV reduction via higher walls augmented by ~15% dFEV reduction via GRR and flood-plain storage, and ~0%-5% (extra) dFEV reduction via NFM; the last figure of

~0%-5% was stated in a public meeting at Kirkstall in early 2019.

- **[C4]** In the text it does refer to these impacts on a storage basis, which is wrong and quite confusing to the lay person – or misleading when factoring in conveyance.

  [R4] Referring to [R**3**], the factoring in of conveyance is indeed considered and so the classification in **[C4]** of the approach as *"wrong and quite confusing"* is not merited since it advocates not only GRR but also a variety of flood-mitigation measures, only one of which is (dynamic) flood-plain storage. Papers **[2,3]** moreover highlight approaches in which none of the mitigation measures itself exceeds ~50% of the total. Also, in **[2,3]**, dFEV has been repeatedly qualified as the *effective* volume in order to contrast it with a static volume (which it is not). Moreover, stakeholders in both France and Slovenia particularly appreciated that expressing each mitigation measure as a (dynamic) volume conveys a sense of size of that measure, also relatively to another, which (sense of size) hitherto was generally missing in communication with stakeholders, decision-makers and the public.

- **[C5]** FEV is concerning also, as it ties its case to volume.

  [R5] As stated in **[R1]**, the term dFEV now supercedes the hitherto-used "*effective volume*", noting that both terms emphasise its foundation on integrated flow rather than on storage/static volume *per se*.

- **[C6]** However, we know that for a given rarity event the volume can change significantly depending on duration, storm coverage and rainfall intensity.

  [R6] As stated in **[R2]**, in **[2,3]** the use is advocated of ensemble forecasting based on a variety of events. However, by mitigating against a rare event involving a combination of a peak water level with a peak flood volume (a temporally integrated discharge/flow), one automatically also mitigates against an event with a (similar) high water level yet shorter duration. In fact, a mixture of GRR, floodwater storage, use of reservoirs and NFM optimally mitigates against both types of events without the need to excessively increase wall heights in cities.

- **[C7]** This means that for the same target SoP using FEV as a descriptor would change depending on the hydrological nature of the scenario you were describing, which becomes quite complicated and probably would undo some of the benefit of a simple message.

  [R7] In **[2]**, the use is advocated of both dFEV and water levels to calculate return periods leading to (slightly) different classifications; in combination with the use of ensemble forecasting this does cover a range of flooding events and scenarios. In the case of ensemble forecasting, one can also represent the mean results as in **[2]** to keep it simple but, additionally, one can convey the uncertainty arising from such ensemble predictions via the slanted lines already included in **[2, Fig. 10]**. Representing uncertainty in a clear manner is something worthwhile for further investigation.

The FEV cost-effectiveness tool can moreover be used either for *a priori* exploration of flood-mitigation scenarios when time and/or computational resources are lacking (often based on data of one flood event or a few flood events), or for an *a posteriori* executive summary of extensive computer predictions for flood mitigation (possibly including uncertainty quantification using ensemble predictions). Within these contexts, in 2019 the dFEV approach explicitly underpinned not only an *a priori* cost-effectiveness analysis of NFM by a Slovenian NGO regarding floods affecting the city of Ljublana, but also an *a posteriori* cost-effectiveness analysis by French civil engineers, thereby supporting communication and decision-making for the municipality of Sophia Antipolis in France.

Hence the dFEV approach offers a hybrid tool somewhere between technical hydraulic calculations and decision-aiding, which often emerge as the challenging parts of the whole design process.

References

[1] Phase 2 Leeds (River Aire) Flood Alleviation Scheme (LFAS2), Report to LCC Executive Board, December 2017. See "Flood alleviation cover report 041217" at host page https://democracy.leeds.gov.uk/ieDecisionDetails.aspx?ID=45047

[2] Bokhove, O., Kelmanson, M.A., Kent. T., Piton, G. and Tacnet, J.-M., A cost-effectiveness protocol for flood mitigation plans based on Leeds' Boxing Day 2015 floods, *Water* **12(3)**, 652-682, 2020. https://www.mdpi.com/2073-4441/12/3/652

[3] Bokhove, O., Kelmanson, M.A., Kent. T., Piton, G. and Tacnet, J.-M., Communicating (nature-based) flood mitigation schemes using flood-excess volume, *River Res. Appl.* **35(9)**, 1402-1414, 2019. https://onlinelibrary.wiley.com/doi/full/10.1002/rra.3507

[4] Bokhove, O., Kelmanson, M.A., Kent, T. A new tool for communicating cost-effectiveness of flood-mitigation schemes, written evidence, document no. FLO0074 (https://committees.parliament.uk/writtenevidence/9641/pdf/) to Defra Flooding Enquiry (https://committees.parliament.uk/work/107/flooding), September 2020.

Onno Bokhove and Mark Kelmanson
October 2nd 2020.

Part 3: Schematic overview of the flood-policy method.