Using flood-excess volume to show that upscaling beaver dams for protection against extreme floods proves unrealistic

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The questions we address in the present aricle are the following: (i) whether (extreme) river floods can be prevented or seriously mitigated by the introduction of beavers in the wild, and (ii) for which river catchments does flood mitigation by beaver activity (not) work? By using the concept of flood-excess volume (FEV) for four rivers in the UK, in the context of five (extreme) UK flood events in the last two decades, we show that even a 10% flood reduction of the FEV, using beaver colonies and beaver dams, requires hundreds of such colonies per river catchment. Given the high number of beaver colonies and dams required for mitigation, we conclude/demonstrate that serious flood mitigation by massive introduction of beaver colonies is completely unrealistic, in stark contrast to statements made in scientific literature and in the media. Furthermore, FEV is valuable beyond its utility as a tool in analysing the efficacy of beaver dams as flood protection: it is demonstrated to be a useful tool for assessing in an easy-to-understand way a variety of flood-mitigation measures, including analysing the scalability of local flood-mitigation measures for overall catchment needs.

Key words: floodwater storage, beaver dams, flood mitigation, upscaling, flood-excess volume

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1. Introduction

In the first decade of the 21st century, and continuing to the present day, a series of devastating river floods have hit the UK, as summarised in the Pitt Review (2008). Within this period, though many rivers flooded and caused widespread damage across the UK, our attention presently focusses on only a few of these flood events. First, the Boxing Day Flood of 2015 in Yorkshire of the River Aire, River Wharfe and River Calder (The Guardian December 2015; Environment Agency 2016, 2018; West Yorkshire combined Authority December 2016), which caused widespread damage across Yorkshire, thankfully without any fatalities. Second, the River Don flood of 2007 in Sheffield (The Guardian 2007), which caused widespread damage and, tragically, three drowning fatalities. Third, the floods of the River Tamar in Devon in both 2012 and 2013. The River Aire and River Calder floods were extreme and classified with return periods of 1:200^{+} years and 1:100 years respectively, and the River Don flood was a flood event with a 1:200-year return period.

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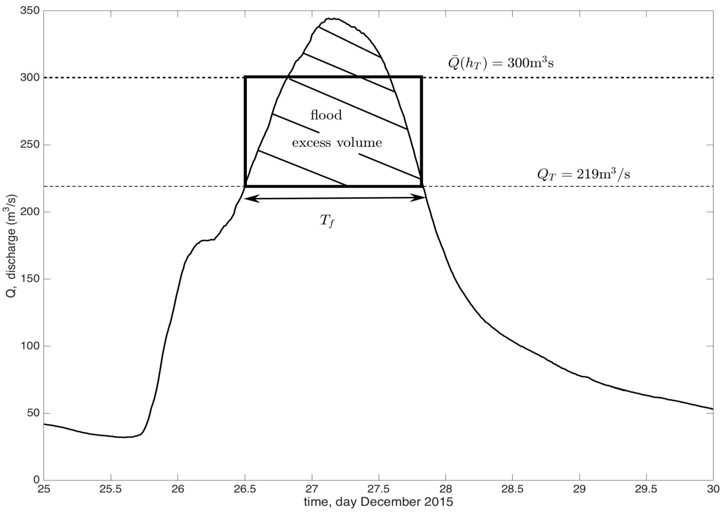

FIGURE 1. The discharge curve $Q(t) = Q\left(\bar{h}(t)\right)$ on the vertical axis versus time t on the horizontal axis is displayed for the Boxing Day 2015 flood of the River Aire at Armley, Leeds, UK. The river level $\bar{h} = \bar{h}(t)$ is measured every 15min at Armley. Given $\bar{h}$, the discharge is found using a rating curve $Q(\bar{h})$, which for the Armley station is established by the Environment Agency (2016b). The flood-excess volume (FEV), here $V_e = (9.34 \pm 0.51)\mathrm{Mm}^3$, is found by determining the hatched "area" under the discharge curve $Q(t)$ above the chosen threshold discharge $Q_T = Q(h_T)$. Here $h_T = 3.9$m is a river level above which (severe) river flooding occurs and the flood duration for this threshold is indicated as T_f, here 32hrs. The rectangle indicated represents a mean (approximation) of this FEV: the product of the difference between the mean $\bar{Q}(h_T)$ and Q_T with the flood duration T_f. See also Bokhove et al. (2018a), from which the figure was taken.

The aforementioned flood events led the UK government and flood practitioners, drawn from academia to consulting firms, to revisit the issue of how to improve flood-mitigation measures, and of how to protect against increased flood risk due to climate change. While climate change predictions do indicate that flood events and intensity will increase for flood events with a return period of 1:100 years or less, *cf.* Sanderson (2010) and the IPCC (2013), work by Hodgkins et al. (2017), and others cited therein, reveals that there is no significant increase (yet) of either flood events or of the intensity for floods with a return period of over 1:100 years. Natural flood management (NFM) has been hailed in the media (Guardian 2017; Pickering 2012) and explored by several academics as well as government agencies, *cf.* Environment Agency Oct. (2017) and Lane (2017). NFM concerns the use of elements and features drawn from nature to mitigate floods. It includes, but is not restricted to: reintroduction of river meandering to slow down the flow and to hold back floodwater; the planting of trees and peat restoration in uplands to hold water, as in a sponge, and to promote evaporation; enhancement of a multitude of small- or larger-scale ponds via leaky dams; and, the planting of shrubs and trees along river banks and beck banks to slow down and to deepen the flow. Finally, another NFM measure mentioned is the encouragement of the construction of leaky dams by beavers in order to enhance storage of floodwater (see Environment Agency Oct. (2017)).

Puttock et al. (2017) and The Guardian (2017) cite several advantages of a particular beaver colony located in a tributary of the catchment of the River Tamar, Devon, UK. The cited advantages include:

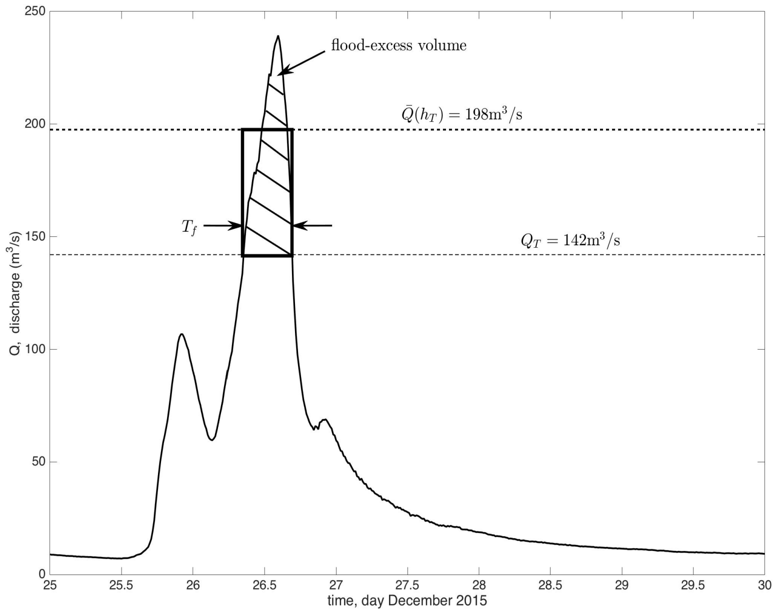

FIGURE 2. The discharge curve $Q(t)$ versus time is displayed for the Boxing Day 2015 flood of the River Calder at Mytholmroyd, UK. As in Figure 1, the flood-excess volume (FEV), now $V_e(h_T = 4.5\mathrm{m}) = (1.65 \pm 0.22)\mathrm{Mm}^3$, is indicated as the hatched "area". The rectangle indicated represents a mean (approximation) of this FEV, as defined in the caption of Fig. 1, with here $h_T = 4.5\mathrm{m}$ and $T_f = 8.25\mathrm{hr}$. Figure taken from Bokhove et al. (2018b).

- a reduction of sediment, nitrogen and phosphate levels, and lower diffuse-pollutant loads going downstream;
- a higher dissolving of organic compounds downstream; and,
- increased (flood)water storage and flow attentuation due to beaver activity within the site.

The beaver colony concerned consisted of 13 dam-pond structures, built over a stretch of 183m, and a maximum of $V_b = (1062\pm23)\mathrm{m}^3 \approx 1100\mathrm{m}^3$ extra water was stored for a flood peak in March 2015, see Puttock et al. (2017), which concluded that ... "*this research forms a solid base, from which to develop an understanding of how beavers may form a 'nature based solution' to the land management, water resource and flooding problems faced by society*". Moreover, based on this very conclusion, the BBC (2017) reported that "*Beavers should be re-introduced to England to improve water supplies, prevent floods and tackle soil loss, a researcher says.*" Against such a background, the questions we aim to address in the present comment are the following: (i) whether (extreme) river floods can be prevented or seriously mitigated by the re-introduction of beavers in the wild, and (ii) for which river catchments does flood mitigation by beaver activity (not) work? Here it is important to note that we accept the benefits of the enhanced, local floodwater storage of $V_b = 1100\mathrm{m}^3$, created by one beaver colony, as a starting point or building block for assessing the potential upscaling of flood-storage volumes on a catchment scale.

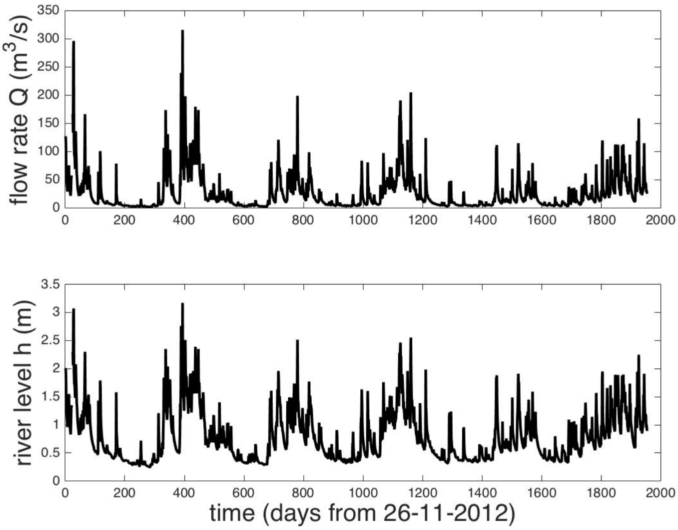

FIGURE 3. River levels and discharge of the River Tamar at Gunnislake from 26-11-2012 until 12-04-2018 respectively. Although not visible at this scale, note that data are missing for at least 16/17/18-12-2012. Flood peaks with daily average river levels over the flood warning level of 2.95m occurred on only 23-12-2012 and 24-12-2013. A severe flood warning is normally issued for levels over 3.45m, which occurred twice in the time period shown; on 22-12-2012, with a maximum river level of 3.58m, and on 24-12-2013 with a maximum river level of 3.46m. A flood alert at full banks is normally issued for a river level of 2.65m (communication via formal request to the Environment Agency).

2. Use of flood-excess volume

To answer these questions we use flood-excess volume (FEV), introduced and analysed by the present authors in Bokhove et al. (2018a), in an analysis of a hypothetical Leeds' flood-alleviation scheme to highlight demonstration of a novel cost-benefit analysis of flood mitigation. In Bokhove et al. (2018b), we illustrated the use of FEV as an efficacious tool to assess various NFM measures in a quantitative manner. FEV is the volume of floodwater in a particular (extreme) flood event that causes the flooding and flood damage. When the FEV, denoted by V_e, equals zero, there is neither flooding nor severe flood damage. The FEV is calculated by choosing an *in situ* river threshold level h_T commensurate with river levels $\bar{h} = \bar{h}(t)$, given or measured as function of time t, at a certain site along the river with h_T sufficiently high for flooding to occur, i.e., with $\bar{h} > h_T$. Corresponding to these river levels $\bar{h}$, discharge rates $Q = Q(t) \equiv Q\left(\bar{h}(t)\right)$ are determined. Given the threshold river level $Q_T = Q(h_T)$, the FEV is the floodwater fraction of the total water volume for which the discharge rates have been larger than Q_T. It concerns the period of flooding T_f for which $Q > Q_T$, or a sequence of such periods comprising one flood event with multiple coherent flood peaks. In general, river levels are measured and the corresponding discharge rates determined via a so-called rating curve, which is a curve relating river level $\bar{h}$ and discharge $Q = Q(\bar{h})$. Rating curves tend to be determined in a phenological manner via (a limited number of) *in situ* field measurements, often combined with numerical modelling, see *e.g.*, Environment Agency (2016b). The FEV can sometimes be calculated almost exactly, within the accuracy of measuring the river level and determining the rating curve, when there are a sufficient number of measurements sampled relative to the variation of the water level in time.

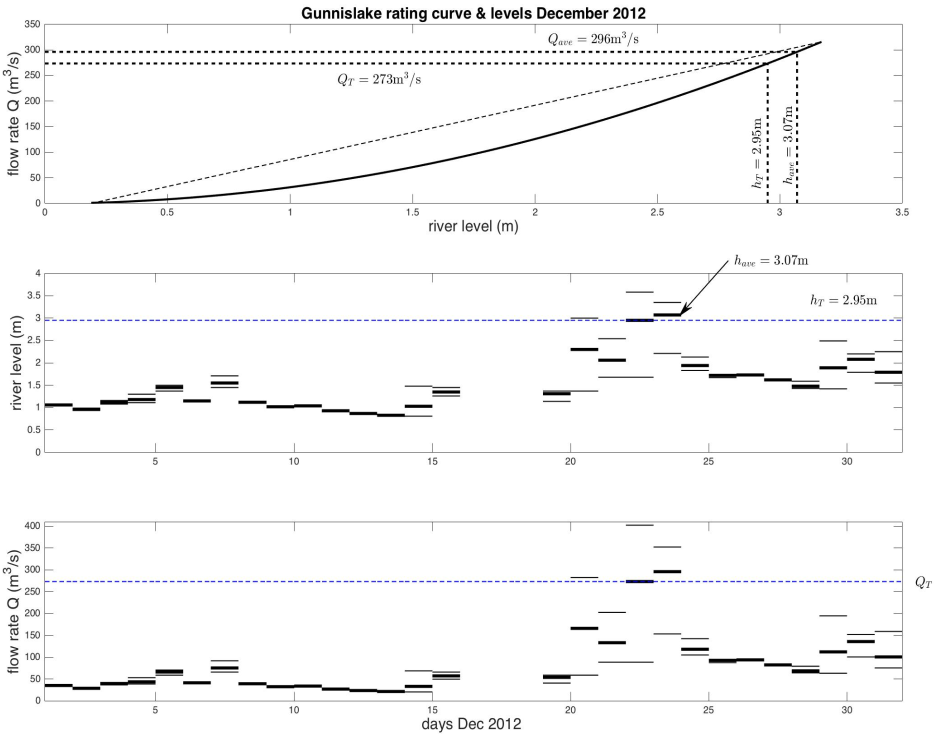

FIGURE 4. The rating curve for the River Tamar at Gunnislake is displayed with discharge on the vertical axis and river level on the horizontal axis (top panel). River levels (middle panel) and discharge rates (bottom panel) around 23-12-2012 are displayed with the flood peak indicated. Measurements are given diurnally, as a daily average (thick lines), daily minimum and daily maximum (thin lines). Dashed lines indicate the flood warning level of $h_T = 2.95$m and corresponding discharge $Q_T = 273\text{m}^3/\text{s}$. The maximum daily average level is 3.07m. Since, based on the daily average data, only one day of flooding is observed here on average, the FEV becomes $V_e = (Q_{max} - Q_T)T_f = 1.958\text{Mm}^3$, with both $Q_{max} = Q_{ave}$ and Q_T; for this flood event, $T_f = 1\,\text{day} = 24 \times 3600\text{s}$.

Graphically, the FEV is the area under the discharge curve over time between $Q(t)$ and the chosen threshold discharge Q_T. For example, in Figs. 1 and 2 are illustrated the FEVs for the Boxing Day 2015 flood events of, respectively, the River Aire and River Calder. The hatched areas in these figures comprise the FEVs, while the rectangular blocks represent the same FEV values approximated using the (mean) discharge rates $\bar{Q}$ and Q_T; both are calculated for threshold river-level values of $h_T = 3.9$m in Fig. 1 and $h_T = 4.5$m in Fig. 2. For these cases, the FEVs calculated are nearly exact, *i.e.* within the accuracy of the $\bar{h}$ and Q obtained, because measurements are made every 15min, which is seen to be frequent relative to the variation of the river level over time. For the River Tamar at Gunnislake, this sampling frequency is too low, since, as we will show shortly, the mean, minimum and maximum river levels are measured only diurnally.

The choice of the threshold values h_T used in in Figs. 1 and 2 is somewhat ambiguous and requires some consideration. We will explain the choices of h_T for the River Aire and River Calder Boxing Day 2015 floods at the river-gauge sites at Armley, Leeds and

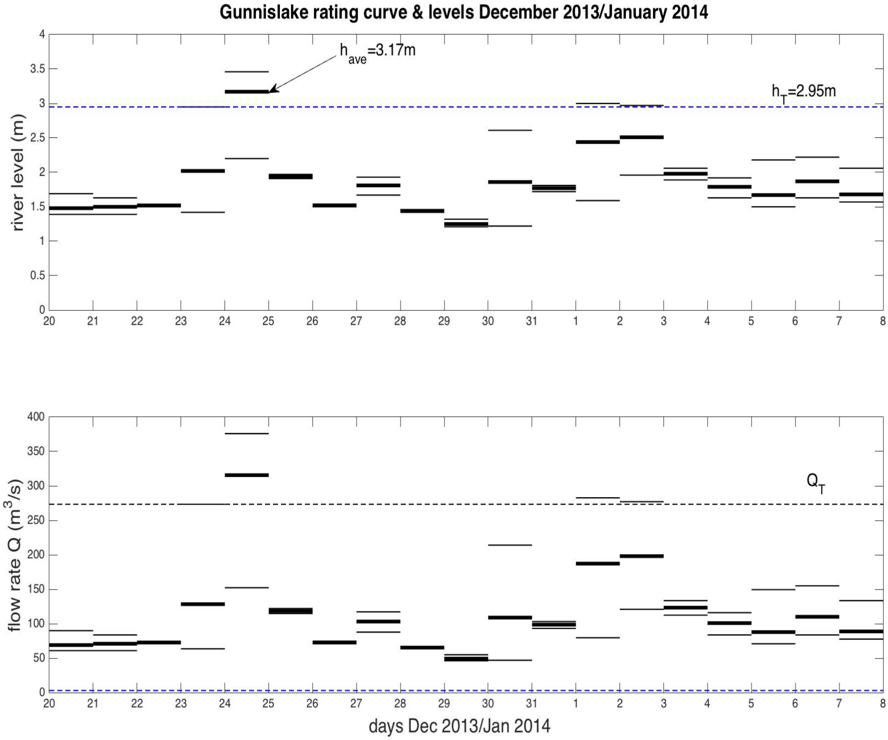

FIGURE 5. The rating curve (top panel) as well as river levels (middle panel) and discharge rates (bottom panel) around 24-12-2013 are displayed with the flood peak indicated. Measurements are given daily, as a daily average (thick lines), daily minimum and daily maximum (thin lines). Dashed lines indicate the flood warning level of $h_T = 2.95$m and corresponding discharge $Q_T = 273\text{m}^3/\text{s}$. The maximum daily average level is 3.17m. Since (*cf.* caption of Fig. 4), based on the diurnally averaged data, only one day of flooding is observed, we estimate the FEV $V_e = (Q_{max} - Q_T)T_f = 3.649\text{Mm}^3$ with again, for this flood event, $T_f = 1\,\text{day} = 24 \times 3600\text{s}$.

Mytholmroyd, at all of which the river gauges are maintained by the Environment Agency. Recent and current data sets are available online and the rating curves and longer time series are made available by the Environment Agency upon request, *cf.* Environment Agency (2016b), under the freedom of information act†.

Concerning the Boxing Day 2015 flood, photographic evidence provided in Bokhove et al. (2018a) reveals that River Aire floodwater started to enter the streets of the industrial area in Kirkstall near the Armley gauge in Leeds at the Armley gauge river level of circa 4.16m. We therefore took the threshold slightly lower, at $h_T = 3.9$m. Official amber flood warnings concerning lower-lying fields and some dwellings in the Kirkstall area start at a mean river-cross-section depth of $\bar{h} = 2.7$m. For the River Aire flood, FEVs $V_e \in [0.0, 25]\text{Mm}^3$ for a range of values $h_T \in [2.7, 5.22]$m have been displayed in Bokhove et al. (2018a). Given that $h_T = 5.22$m is the peak river level, the FEV is necessarily zero for this threshold.

† We thank the Environment Agency for kindly providing the data sets, rating curves, and discussion and information on the error bars involved of their river gauges at Armley, Mytholmroyd, Sheffield Hadfields and Gunnislake. The inferences and conclusions made in this comment are our own.

Concerning the river-level gauge at Mytholmroyd, houses start to flood at $\bar{h} = 4.0$m, when a flood warning is issued, *cf.* information on the public gauge site, while (O.B. recalls that) a major flood alarm used to be raised at 4.85m. We therefore chose $h_T = 4.5$m in Bokhove et al. (2018b), also to reach a slight lower value of the FEV, which led to more favourable relative contributions as a fraction of the relevant FEV for various NFM measures. For the River Calder flood, FEVs in the range $V_e \in [0.0, 2.7]$Mm^3 for a range of values $h_T \in [4.0, 5.65]$m have been displayed in Bokhove et al. (2018b).

Since the beaver colony in Puttock et al. (2017) resides in the catchment of the River Tamar, we analyse flood data of that river in Gunnislake, further downstream of the tributary that contains the beaver colony. River level and discharge data of the River Tamar at Gunnislake are displayed in Fig. 3 for the period from 26-11-2012 until 12-04-2018. In contrast to the Aire and Calder river-level data, the daily average, minimum and maximum sampling frequency is too low to capture the actual variation in the river level. This becomes clear from the representations in Figs. 4 and 5, where we have necessarily displayed these daily data over two restrictive time periods — around the two highest flood peaks on 23-12-2012 and on 24-12-2013 in this limited record — as piecewise-constant horizontal lines of length one day. The average value per day has been displayed by a thick line, sandwiched by the thin lines denoting the minimum and maximum values measured on that day. The Environment Agency employs the following warnings: a flood alert at full banks is issued for a river level of 2.65m; a flood warning level is issued when $\bar{h} > 2.95$m; and, a severe flood warning is issued for levels over 3.45m. The latter occurred twice in the period of data shown: on 22-12-2012, with a maximum river level of 3.58m; and, on 24-12-2013, with a maximum river level of 3.46m. Note that the first maximum occurred on the day before the maximum daily average was reached. Given these three daily data — the mean, minimum and maximum river levels — we could (try to) reconstruct a (piecewise-) continuous river-level curve but, given the usual error bars in the rating curve and our purpose of providing estimates, such an exercise is deemed not to be valuable. Given the above information, we chose the flood-warning level $h_T = 2.95$m as our threshold (communication via formal request to the Environment Agency).

In Table 1, we have provided the FEVs for four rivers and five floods (as two floods peaks are used for the River Tamar), also including one for the River Don 2007 flood in Sheffield for the river-gauge station Sheffield Hadfields (Bokhove et al. 2018b). Given the highest estimate of the enhanced floodwater storage of $V_b = 1100$m^3 by the series of beaver dams in Devon (see information in Puttock et al. (2017)), we have estimated how many beaver colonies of the same size as the one in Devon would be required to provide $100\%, 50\%$ and 10% flood mitigation for the five tabulated floods. In all cases, full flood protection requires thousands of beaver colonies and 10% flood mitigation by beaver dams requires, of course, hundreds of beaver colonies. To obtain estimates of the number of beaver dams and length of tributaries required per respective catchment, one has to multiply these number by 13 and 183m respectively. This, then, leads to a massive number of beaver dams and long length estimates of river tributaries jam-packed with dams. Such length estimates are of course incorrect and far too short. In (Ribic et al. 2017, Fig. 2), data per stretch of river or tributary are provided for the beaver colony density in North America: the natural number density of beaver colonies ranges from one colony every 3km to one every 20km. Consequently, we have to multiply the number of beaver colonies by a factor of at least 3km to 20km in order to obtain length estimates that give the animals sufficient territory.

River -	flood date(s) -	V_e Mm^3	h_T m	V_e/V_b -	$0.5V_e/V_b$ -	$0.1V_e/V_b$ -
Aire	26-12-2015	9.34 ± 0.51	3.9	8490	4246	849
Calder	26-12-2015	1.65 ± 0.22	4.5	1500	750	150
Don	25/26-06-2007	3.00 ± 0.24	2.9	2727	1363	272
Tamar	23-12-2012	1.96 ± 0.20	2.95	1780	890	178
Tamar	24-12-2013	3.65 ± 0.36	2.95	3317	1658	321

Table 1. For four UK rivers and four different floods, five FEVs V_e are given for the threshold levels h_T indicated. The rivers are: the Aire, Calder, Don and Tamar, and the gauge data used to calculate the FEVs were located at Armley, Mytholmroyd, Sheffield Hadfields and Gunnislake respectively. The four floods are the Boxing Day flood of 2015 for the River Aire and River Calder, the 2007 flood of the River Don, and the December 2012 and 2013 floods of the River Tamar. The extra storage volume obtained behind the beaver dams of one beaver colony in Devon, on a tributary that is part of the River Tamar catchment, was estimated in Puttock et al. (2017) to be $V_b \approx 1100\text{m}^3$. We therefore added columns with estimates of the number of (equal-size) beaver colonies required in each respective catchment that would offer $100\%, 50\%$ or 10% flood mitigation via floodwater storage behind (a potentially huge number of) beaver dams, with the relevant FEV V_e being normalised with respect to V_b, *i.e.*, V_e/V_b, $0.5V_e/V_b$ and $0.1V_e/V_b$. With the number of beaver dams required ranging from 100s (last column) to 1000s (fifth column), the clear and inescapable conclusion is that flood mitigation by floodwater storage behind beaver dams is not a viable option to protect against extreme flood events.

3. Conclusions

To conclude, we return to the questions posed at the beginning of this article, to wit: "*(i) whether (extreme) river floods can be prevented or seriously mitigated by the re-introduction of beavers in the wild and (ii) for which river catchments does flood mitigation by beaver activity (not) work?*"

Regarding question (i), the overarching conclusion of our analysis using FEVs for four different river catchments in the UK is that a 10%, let alone 100%, reduction of extreme flood events by mass introduction of beaver colonies as flood mitigation in the (UK) river landscape is demonstrably unrealistic, by two or three orders of magnitude. Any statements made to the opposite effect, as in Puttock et al. (2017) and BBC (2017), have been misleading†. The central challenge with some NFM measures, including here NFM by enhanced floodwater storage via beaver dams, is that they do not at all scale up to the catchment-level needs.

Regarding question (ii), our conclusion that flood mitigation by beaver dams does not scale up holds for the River Aire, River Calder, River Don and River Tamar, not only for more serious flood events but also for flood events as small as one tenth of the size of their respective FEVs. But our FEV analysis is more revealing and general, beyond the particularisation of analysing the effectiveness of beaver dams: it reveals that straightforward estimates of the effectiveness of various flood-mitigation measures can be readily understood and visualised as a fraction of the FEV to be reduced. Cost-benefit analyses based on FEV have been performed for various flood-alleviation schemes

† The efficacy of FEV as a broadly comprehensible concept has been evident in several discussions with members of the British public on flood mitigation with beavers whilst explaining the concept of FEV. Stating the FEV value in terms of millions of cubic metres for a characteristic flood event and subsequently dividing by $V_b \approx 1000$m or 1100m usually leads to the quick realisation by the public that upscaling of the number of beaver colonies to get significant flood mitigation in a river catchment is quite unrealistic.

either proposed or hypothesised in Bokhove et al. (2018a,b). It must be said that our upscaling estimates provided here are upper bounds because we have assumed that, even when introducing a multitude of beaver colonies, each dam remains fully effective, thus excluding beaver-dam failure or mass abandonment of beaver colonies, and so forth. In addition, a high density of beaver colonies is hardly sustainable in an urban or semi-rural UK site.

Finally, there are plenty of reasons why the research of Puttock et al. (2017) is very welcome and extremely valuable. For example, a significant increase of beaver colonies across the UK would, in the present (political and social) climate, not only be extremely welcome from a wildlife perspective, but also it would be indicative of a healthy environment: we are certainly looking forward to progress in this direction. But despite the many reasons to welcome more beavers in the UK environment, serious flood mitigation by enhanced floodwater storage behind beaver dams is, as we have shown here, not one of them. It is similarly unrealistic to upscale or amplify some of the other mentioned, local benefits of a beaver colony, such as sediment storage and improved water quality due to an increase in biodiversity, to catchment-level needs. Though flood mitigation needs to be done, it can only be as a result of engineering and carefully managed and planned NFM projects; therefore, figuratively speaking, "we are the real beavers"!

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