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O. Bokhove, M.A. Kelmanson, T. Kent, Guillaume G. Piton, J.M. Tacnet

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Communicating (nature-based) flood-mitigation schemes using flood-excess volume

Onno Bokhove[1] | Mark A. Kelmanson[1] | Thomas Kent[1] | Guillaume Piton[2] | Jean-Marc Tacnet[2]

[1]School of Mathematics, University of Leeds, Leeds, UK

[2]Univ. Grenoble Alpes, IRSTEA, UR ETGR, Centre de Grenoble, Saint-Martin-d'Hères, France

Correspondence
Onno Bokhove, School of Mathematics, University of Leeds, Leeds, LS2 9JT, UK.
Email: O.Bokhove@leeds.ac.uk

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Abstract

As interest mounts in nature-based solutions (NBS) for flood mitigation as complementary options to civil-engineering measures, possible flood-protection strategies have become more diverse and hence complicated to assess. We offer a straightforward and educational protocol targeted for effectiveness analysis and decision making involving stakeholder participation. It is based on the concept of flood-excess volume (FEV), the volume exceeding a threshold and generating flood damage, and explores what fraction of FEV is reduced, and at what cost, by particular flood-mitigation measures. Quantification and interpretation of cost scenarios are facilitated using a graphical display that is easy to understand and encapsulates concepts of flood magnitude, FEV and protection-measures efficacy. It is exemplified for two recent extreme-flood events on the River Calder in Mytholmroyd (Yorkshire, United Kingdom) and the River Brague in Biot (Alpes-Maritimes, France). Each case has different flood-mitigation measures such as natural water-retention measures, tree planting, river-bed widening, or use of reservoirs and floods walls. Our straightforward protocol enables fast, quantifiable and easy-to-understand exploration of protection strategies using multiple measures, and in doing so highlights the issue of NBS scalability.

KEYWORDS
cost-effectiveness, flood protection, flood-excess volume, natural water retention

1 | INTRODUCTION

There is an increasing interest in using Natural Flood Management (NFM) to alleviate current and future risks of river and coastal flooding, more broadly denoted as nature-based solutions (NBS). The European Commission (2018) defines "Nature-based solutions to societal challenges as solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions."

Examples of NFM are run-off attenuation features, for example, leaky-debris dams, planting of peat and trees, remeandering of brooks and rivers, and planting of trees and bushes along river banks for a comprehensive overview see Environment Agency (2017b) and Stosser et al. (2015). The idea of NFM is to slow down the flow by increasing flood depths, in places where this is deemed acceptable, thus reducing flood peaks further downstream at critical locations, for example, river levels near or through villages and cities. The giving-room-to-the-river (GRR) programme of enhancing the flood-plain volume (van Roekel, 2014) also fits within the wider remit of NFM: it uses naturally suitable river locations to create extra floodwater storage or conveyance capacity, for example, by the construction of fixed or moveable weirs or widening and deepening a flood plain, including reopening old river meanders. Evidence for the effectiveness of NFM is case-specific, given the diversity of contributing factors.

Collective slow down of flood peaks in tributaries may not necessarily lower the main flood peak since synchronisation of flood peaks can lead to adverse effects with increased flood peaks and flooding further downstream (Cabaneros et al., 2018). Moreover, in wet periods before large flood events, soil can become oversaturated such that the run-off of extra rainfall is nearly instantaneous (Environment Agency, 2016a). Most of the literature on NFM provides qualitative descriptions of flood-reduction effects and cobenefits, but seldom quantitative assessments and clear recommendations on how to quantify reductions on a catchment scale (Environment Agency, 2017b; Stosser et al., 2015). Because decision making in land-use planning and flood-protection management involves participatory approaches and stakeholder involvement having multifaceted effects, there is a growing need for approaches to educate people in understanding the volumes and costs involved in floods and their mitigation.

A sometimes-neglected aspect of NFM is that proposed methods are difficult to scale up in a robust manner, for example, attenuation features such as leaky dams tend to be small individually, implying that many features are required before effects are significant for larger floods on a catchment scale. Such upscaling also increases and complicates maintenance. Tree and peat planting requires enormous areas before mitigation effects may become significant for larger flood events. Even then, there is a lack of evidence to suggest that increased tree coverage reduces flood risks (Carrick et al., 2018). Besides showing beneficial effects in small-scale NFM pilot studies (Environment Agency, 2017b), it is important to obtain first estimates of NFM's effectiveness and reliability on grander catchment scales for extreme-flood events. Contrastingly, GRR programmes generally concern larger volumes.

For both NFM and civil-engineering measures, first assessments of the effectiveness of flood-mitigation strategies can be quantified straightforwardly using flood-excess volume (FEV; see Hui & Lund, 2015; Schneider, 2015; Bokhove et al.,2018a). FEV concerns the fraction of the total volume of river discharge, over a certain period, which caused flooding at a certain river location during an extreme event. It implies that in situ river flood levels have exceeded a certain threshold river level h_T yielding associated excess discharge rates. FEV is the flood volume one wishes to reduce to zero in flood-mitigation approaches in order to avoid flood damage, for example, by raising flood-defence walls along a river, effectively raising h_T; increasing the river-bed section, enabling more discharge to be conveyed under a similar water depth; or, holding back water or slowing down the flow by upstream flood-mitigation measures, thus lowering FEV either by a significant fraction or entirely by the cumulative effect of several mitigation measures.

The goal here is to communicate flood-mitigation analyses based on NBS and civil-engineering methods for (a) the 2015 Boxing Day flood of the River Calder in Mytholmroyd (Yorkshire, United Kingdom), which flows into the North Sea via the Humber estuary and (b) the 2015 flash flood of the River Brague (Alpes-Maritimes, France), which flows into the Mediterranean Sea near Antibes. Our analysis is intended to provide an insightful and accessible protocol for assessing flood mitigation, aimed at increasing public understanding and assisting policy makers in decision making. We build upon the analysis of a (hypothetical) flood-alleviation scheme in Bokhove et al. (2018a), in which more available physical and economic data is incorporated. The paper outline is as follows. In Section 2, FEV and available flood-storage volume are revisited to allow use in subsequent sections. In Section 3, FEVs are calculated for the River Calder and the River Brague floods of 2015. Subsequently, several flood-mitigation measures proposed within these river catchments are analysed in Section 4, with conclusions drawn in Section 5.

2 | TOOL: FLOOD-EXCESS VOLUME

The FEV of a river in flood is defined as the water volume causing flood damage at a certain station due to river levels $\bar{h}$ exceeding a relevant threshold h_T. This choice of flood quantification is such that, for $\bar{h} > h_T$, some or major flooding occurs. Conceptually, FEV offers a straightforward and comprehensible means of quantitatively underpinning flood-mitigation strategies. It is presently assumed that the stage–discharge relationship of the river is known in terms of a recorded and accurate time-series (see also Bokhove et al., 2018a). Given an in situ rating curve $Q = Q(t)$ explicitly as function of time t over a flood duration T_f, or implicitly as a function $Q = Q(\bar{h})$ of the in situ river level $\bar{h} = \bar{h}(t)$, the approximation of FEV used (which comprises the shaded and hatched areas in Figure 1a) is

$$V_e \approx \sum_{k=1}^{N_m} \left(Q(\bar{h}_k) - Q_T)\right) \Delta t, \tag{1}$$

in which $Q_T = Q(h_T)$. In the limit of an infinite number of river-level data h_k, that is, when $\Delta t = T_f/N_m \to 0$ as $N_m \to \infty$, FEV approximation (1) becomes an integral. In general, rating curves are not exact due to errors in the relation $Q(\bar{h})$ and measurement errors in $\bar{h}_k$. Generally, river levels $\bar{h}$ are measured and, using theoretical or phenomenological rating curves (Bokhove et al., 2018a; Environment Agency, 2016b), they are converted into discharge rates $Q(t) = Q\left(\bar{h}(t)\right)$.

2.1 | Available flood-storage volume

Available flood-storage volume is the extra flood-storage volume gained above the flood capacity that a flood-storage site has for a flood of a particular return period. This available flood-storage volume changes as a function of the return period of the flood event; for floods with higher river levels and longer duration, it is less than for floods with lower river levels and shorter duration. Leaky dams slow the flow and increase the upstream water level; their flood-storage capacity is time-dependent because the upstream water levels increase rapidly during a flood event and slowly decrease afterwards. Nonetheless, leaky dams may lead to a reduction of FEV, and hence, there is always an effective storage volume. To estimate the latter, we hereafter ignore the time dependence of the flood volume stored in the preliminary estimates, thereby implicitly assuming that temporal variations are small within the flood duration T_f. In addition, the actual public NFM project quoted in Section 4.1.1 specifies only the overall/effective storage volume of the flow attenuation features (see also the River Don case in Bokhove et al., 2018b).

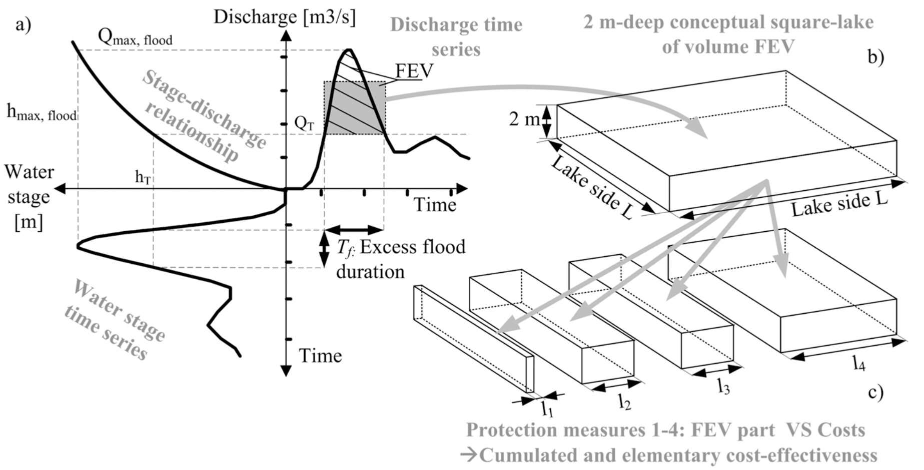

FIGURE 1 Conceptual flood-excess volume (FEV) representations. (a) Three-panel graph highlighting FEV: (bottom-left) view of river-level time series around a flood event; (top-left) stage–discharge relationship arising from (top-right) discharge data, in which FEV is the hatched "area" between the discharge curve $Q(t) = Q(\bar{h}) = Q\left(\bar{h}(t)\right)$, displayed vertically as function of time horizontally, and a chosen threshold discharge $Q_T = Q(h_T)$ with exceedance time T_f, involving in situ temporal river levels $\bar{h} = \bar{h}(t)$. (b) FEV square-lake representation as a $D = 2$ m-deep square lake, with side-length $L = \sqrt{FEV/D}$, to facilitate visualisation of FEV "size." (c) FEV-effectiveness assessment computed for each measure as equivalent FEV fraction, represented as side l_i of the square lake

2.2 | Square-lake representation: a cost-effectiveness communication tool

The three-panel graphs in Figure 1 readily illustrate the FEV concept and offer an approximate sense of the water volume responsible for flooding, though this might not be sufficient to facilitate discussion with all stakeholders and decision makers sufficiently aware of the "problem size". Because water volume can be hard to appraise quantifiably, the "square-lake" representation has been proposed (Bokhove, Kelmanson & Kent, 2018b) as a conceptual object facilitating such appraisal: FEV volume is represented as that of a square lake of depth 2 m, that is, a "buildable-scale" reservoir required to store the FEV; such a visualisation is more meaningful than a volume in comparison with a typical river's length or valley width.

The analysis is further refined by splitting the square-lake FEV into a set of protection measures. The capacity of each measure to store, or deal with a volume by conveying it, is finally computed, whence the cost of each measure can be estimated. A straightforward cost-effectiveness assessment is then performed by considering the ratio between the FEV assigned to a measure and its costs. The cost-effectiveness is then measured in terms of percentage costs of FEV. This approach is encapsulated in the graphical representation of the flood process exemplified in Figure 1, which comprises:

- a three-panel graph displaying the stage–discharge relationship along with the discharge (hydrograph) and measured water–stage–time series highlighting flood duration, peak discharge, water depth, threshold values, and FEV (with corresponding error); and,
- a square-lake representation as a 2 m-deep basin (i.e., approximately human height) with the same capacity as the FEV, partitioned according to the estimated contribution of various protection measures and overlaid with costs.

3 | DATA: FEV ANALYSIS

River-level data from the River Calder at Mytholmroyd for the Boxing Day Flood in 2015 and from the River Brague 2015 flood in France are analysed (see Figure 2). A clarification is that we present all three-panel figures with direct river-level measurements, the rating curve, and inferred discharge relations in one graph, thereby explicitly displaying the main associated errors, which build upon the FEV concept and are relevant for the ensuing cost-effectiveness analyses.

The winter of 2015/2016 in the United Kingdom is widely recognised as an extreme hydrological episode, for the magnitude, spatial extent and impacts of the flooding that occurred (Barker et al., 2016). On December 26 and 27, 2015, an extreme-flood event was recorded for both the River Aire and River Calder in Yorkshire, United Kingdom—the so-called Boxing Day Flood—whose severity elicited high-profile coverage in national media (e.g., Gayle & Gunter, 2015). The Boxing Day 2015 events had approximately 1:200$^+$ - and 1:100$^+$-year return periods for the River Aire and Calder respectively (i.e., we consider these return periods as those given in Environment Agency, 2016a). Although both events were extreme and outside the range of data records, their return periods could be estimated using extreme-value theory (Coles, 2001).

The River Brague flows in a hilly environment on the French Riviera between the cities of Nice and Cannes into the Mediterranean Sea. It has a 68 km^2 catchment with rural/suburban headwaters, a forested central part, and urban lowlands. On October 3, 2015, severe rainfall caused the Brague to burst its banks, triggering dramatic floods in the region. Within several catchments, more than 20 people tragically died, 550–650 M€ of insured damages accrued, and concomitant complications cascaded onto transportation, communication, and energy networks (Préfécture des Alpes-Maritimes, 2015). These events unfolded extremely rapidly and were of excessive magnitude. For example, the Brague catchment experienced peak discharges with a 1 : 100$^+$-year return period and the Brague hydrological station (Y5605210) stopped functioning over a depth of 3.15 m

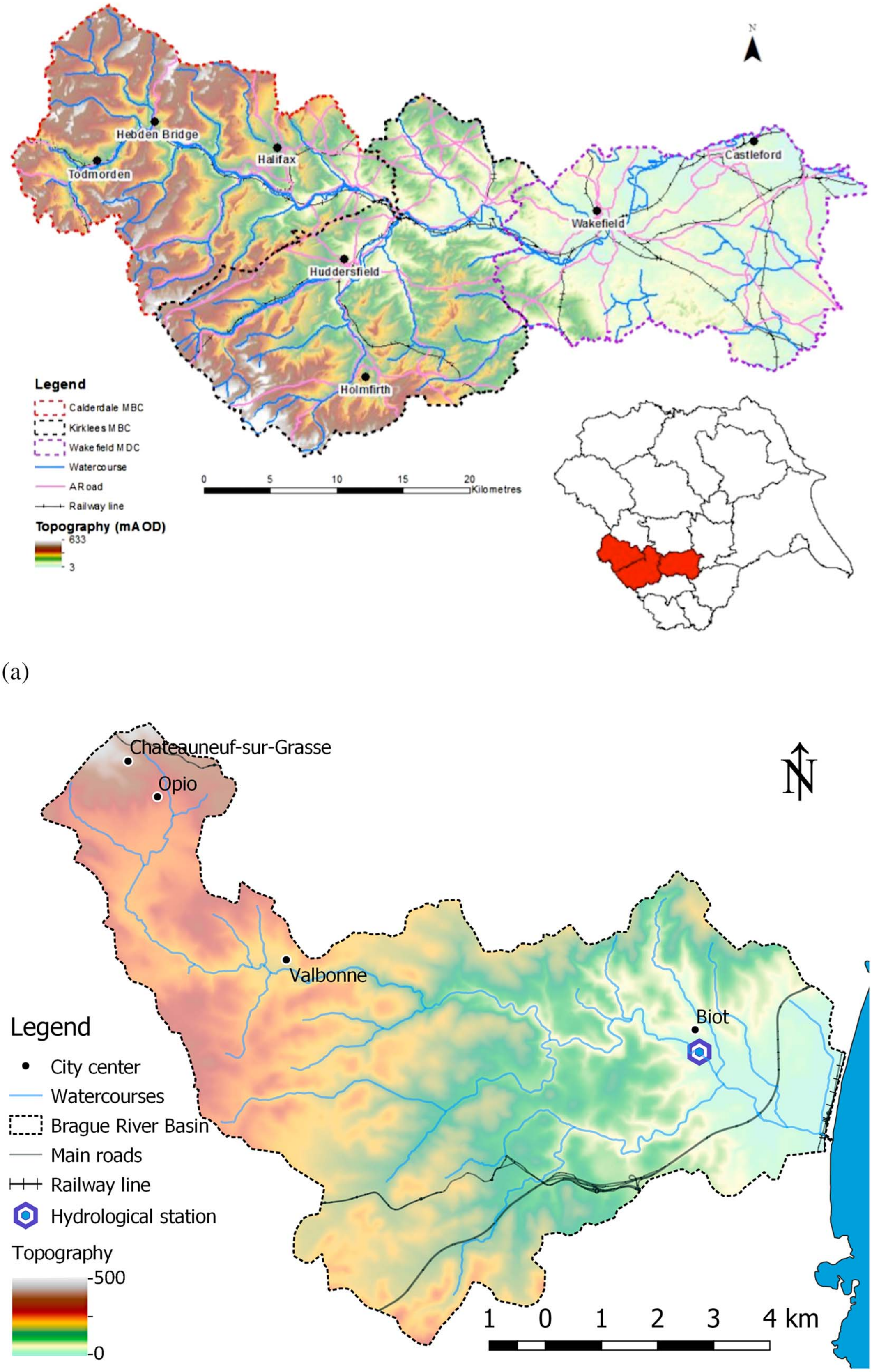

FIGURE 2 (a) Calder and (b) Brague catchments. Figure courtesy: JBA report "Calder Catchment strategic flood risk assessment" Vol. I, 2016 and IGN data (BD ALTI 25m, BD Carto and BD Carthage)

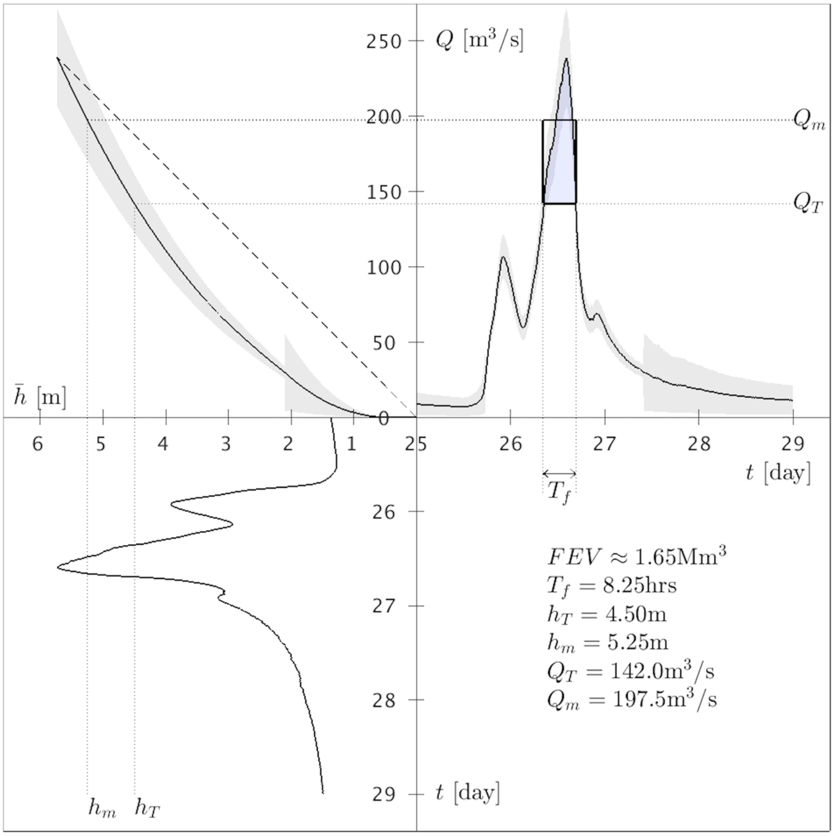

FIGURE 3 Visualisation of 2015 flood data (River Calder) of (top-left) the rating curve and its linear approximation; (bottom-left) reoriented view of the river-level time series, and (top-right) discharge data, in which flood-excess volume (FEV) is the shaded "area" between the discharge curve $Q(t) = Q(\bar{h}) = Q\left(\bar{h}(t)\right)$, displayed vertically as function of time t (day in December 2015) horizontally, and chosen threshold discharge $Q_T = Q(h_T)$. It involves in situ temporal river level $\bar{h} = \bar{h}(t)$. The rectangle (top-right) represents a mean (approximation of the) FEV based on mean and threshold discharges and a flood duration $T_f = 8.25$ hr, that is, $V_e = (Q_m - Q_T)T_f$. Horizontal dashed lines indicate chosen threshold and mean levels and corresponding discharges, obtained graphically via the rating curve. Errors are indicated by grey shading [Colour figure can be viewed at wileyonlinelibrary.com]

when, at 19:30, a flow rate of 143 m^3/s was measured[1]; however, a maximum depth of 5.60 m was measured during the post-event field campaign (Préfécture des Alpes-Maritimes, 2015). Despite several strong postmillennial floods, for example, in 2005 and 2011, the 2015 event had a markedly higher magnitude and more serious consequences on all fronts, that is, flooded area extension, fatalities, and cumulative insured damages. Most of the damage within this catchment occurred in Biot and Antibes, two lowland municipalities, which both experienced post-flooding insured damages exceeding 50 M€ .

3.1 | River Calder Boxing Day 2015 flood

FEV is first exemplified for the River Calder Boxing Day 2015 flood, using stage data from the Mytholmroyd gauge (located just downstream of Hebden Bridge in Figure 2a). The river level (at 15-min intervals), rating curve, and discharge data are given in Figure 3 with $h_T = 4.5$ m estimated to be the threshold for heavy property flooding. The corresponding FEV and its error (using error-propagation techniques) are

$$V_e(h_T = 4.5\mathrm{m}) \approx (1.65 \pm 0.60)\ \ \mathrm{Mm}^3, \tag{2}$$

or the capacity of a square lake of depth 2 m and side-length 908 m. For the first stage of the rating curve, error bars of 84.9% for Q are reported; for the second stage, 13.6% for Q, and for the last stage and beyond, error bars are not available (Environment Agency, 2017a). The error estimate in (2) therefore uses the 13.6% of the second stage to calculate the resulting 36% overall error as a parametric placeholder. We stress that FEV is clearly a function of the chosen threshold h_T; Figure 4 highlights its dependence on relevant choices of $h_T \in [4, 5.65]$ m; cf. the Mytholmroyd gauge on https://www.gaugemap.co.uk.

3.2 | River Brague 2015 flood

Following the River Brague 2015 flood, the regional authority, assisted by a panel of experts, performed a comprehensive appraisal of the resulting hazards and damages (Préfécture des Alpes-Maritimes, 2015). Field measurements were conducted to compute peak discharges based on topographical sections, flood levels, and river-bed roughnesses. The peak discharge at the Biot station was estimated to reach 240 m^3/s within the envelope 185–295 m^3/s (Lebouc & Payrastre, 2017), higher than the 1:100-year-return-period peak discharge of 200 m^3/s (Préfécture des Alpes-Maritimes, 2015). A further study using radar rainfall data and a hydrological model of the catchment yielded hydrographs of the event (Lindénia, 2016). Downstream tributaries also experienced major events, aggravating flooding in Antibes. As a consequence, an ongoing programme of updating flood-risk mapping has ensued since 2015, and a numerical model of flooding built and calibrated on the event: this has demonstrated that flooding may occur in Biot for any discharge higher than a 1 : 30-year-return-period event, that is, $Q > 135$ m^3/s (Cabinet Merlin, 2016). Consequently, we therefore compute h_T such that $Q(h_T) = 135$ m^3/s in the bed configuration considered.

FEV analysis admits a straightforward assessment of several protection strategies based on retention measures and flood-wall raising. Flood walls were raised to the height necessary to contain the remaining discharge not stored in retention areas. In such a scenario, the

[1]Data available at `http://www.hydro.eaufrance.fr/stations/Y5605210` for station "La Brague à Biot [Plan Saint-Jean]", catchment size 41 km^2.

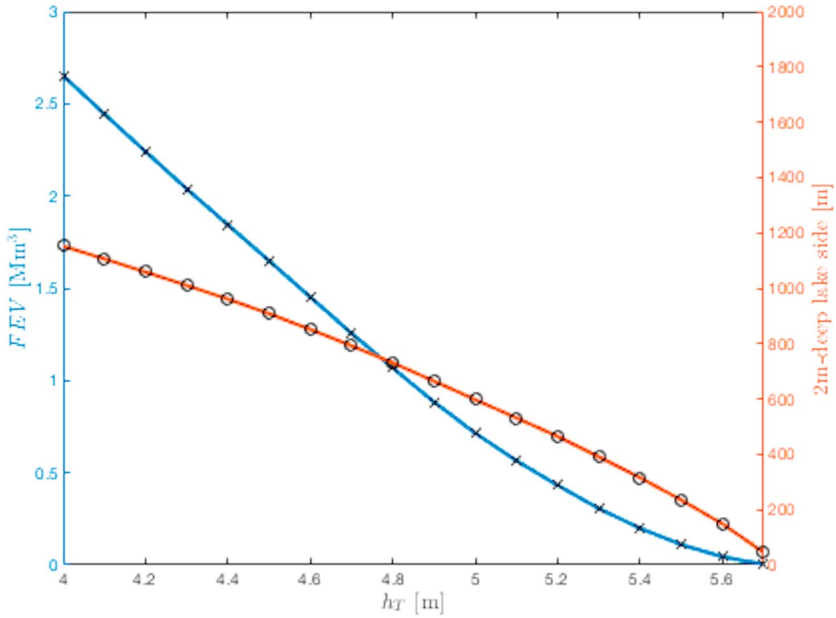

FIGURE 4 Flood-excess volume (FEV; crosses) and square-lake side (circles) as function of h_T for the River Calder flood [Colour figure can be viewed at wileyonlinelibrary.com]

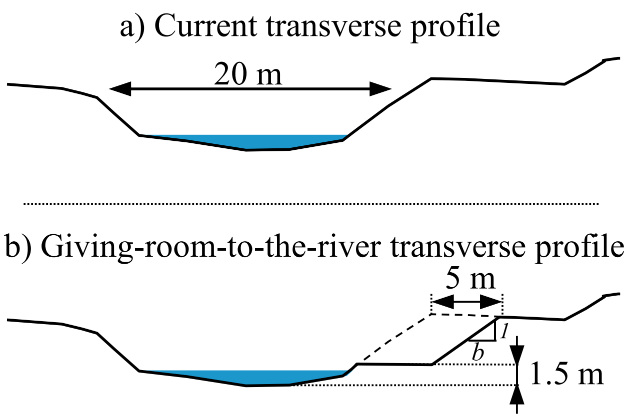

FIGURE 5 Simplified transverse profiles of the Brague river: (a) current profile and (b) profile of the giving-room-to-the-river scenario, 5 m wider at 1.5 m high, with the same (prewidened) bank slope b [Colour figure can be viewed at wileyonlinelibrary.com]

river-bed section remains untouched, flood walls merely increasing the level above which flooding starts. An alternative to wall raising is GRR, that is, an increase of the river width and, correspondingly, discharge capacity for a similar water depth (see Figure 5). Such an option can also be analysed within the FEV approach by changing the stage–discharge relationship. In Figure 6, both actual (solid lines) and new (dashed lines) stage–discharge relationships are shown in the three-panel visualisation format of Figure 3. To obtain this new relationship, compound-channel theory has been applied (Te Chow, 1959) with a W_{GRR} = 5 m-wide increase of the section at a height of z_{GRR} = 1.5 m above the river-bed base level. Using current stage–discharge relationship $Q = Q(\bar{h})$, the flow in the widened section is computed by Manning's equation, adding its discharge to current bed capacity to compute the total discharge

$$Q_{GRR}(\bar{h}) = Q(\bar{h}) + \frac{\sqrt{S}((\bar{h} - z_{GRR})W_{GRR})^{5/3}}{n(W_{GRR} + (\bar{h} - z_{GRR})\sqrt{1+b^2})^{2/3}}, \tag{3}$$

using longitudinal river-bed slope S = 0.004, transverse bank slope b = 1.3 (estimated here on the current section), and Manning coefficient n = 0.043 (calibrated here on the current stage–discharge relationship).

Parameters for the FEV analysis are provided by both the current and enhanced bed sections along with the discharge curve (Figure 6, top-right) and the river-level time series (Figure 6, bottom-left) for a given rating curve (Figure 6, top-left). The FEV for the chosen threshold level of h_T = 3.06 m is selected such that $Q(h_T)$ =135 m^3/s, whence the current FEV of V_e = 0.488 Mm^3 reduces to $V_{e,GRR}$ = 0.352 Mm^3 as a result of the river-bed widening. An estimate of uncertainty in FEV follows from computing upper and lower envelopes using a correction of the flood hydrograph proportional to the peak-discharge envelopes provided by Lebouc and Payrastre (2017), that is, $V_e(h_T = 3.06 \text{ m}) \approx (0.488 \pm 0.311)$ Mm^3 and $V_{e,GRR}(h_T = 3.06 \text{ m}) \approx (0.352 \pm 0.286)$ Mm^3. This uncertainty in the water-level data (±14%) or hydrology (±23%) greatly exceeds that in the rating curve, which is 5% according to the source website, leading to appreciably higher error estimates than those for the River Calder at Mytholmroyd.

3.3 | Square flood-excess lake analysis

By analysing the flood data from different United Kingdom and French rivers for different flooding events (Bokhove et al, 2018a, 2018b), the following FEVs $V_e \approx (9.34 \pm 1.50, 1.65 \pm 0.60, 3.00 \pm 0.71, 0.488 \pm 0.311)$ Mm^3 were found for chosen threshold levels of $h_T = (3.9, 4.5, 2.9, 3.06)$ m, respectively, for the Rivers Aire and Calder (2015 floods), the River Don (2007 flood) in Sheffield, United Kingdom, and the River Brague in France (2015 flood). These volumes can also be expressed as capacities of 2 m-deep square lakes with side lengths of (2161,908,1225,494) m, respectively. Between these rivers, there is an order of magnitude difference in FEVs, see Table 1. The perspective and visualisation of FEVs as square lakes with realistic depths is useful when considering and analysing flood-mitigation strategies. Given the square-lake size, the width and length of the river valley, and the size of the catch-

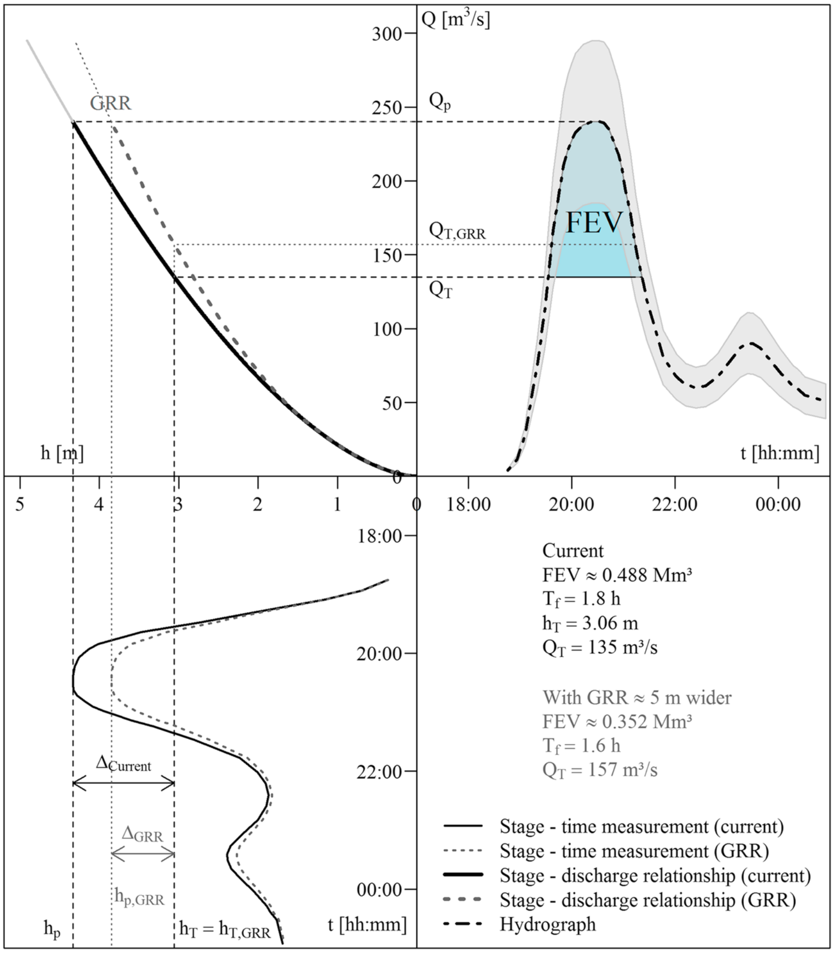

FIGURE 6 Flow rate and river-level data of River Brague at the Biot station. Integrated visualisations (cf. Figure 3) from the Brague catchment for the October 3, 2015, flood event. Solid- and thick-dashed lines show respectively the current (V_e = 0.488 Mm^3) and 5 m-wider bed ($V_{e,GRR}$ = 0.352 Mm^3) stage–discharge relationships. The (reoriented) three-panel complex also depicts changes in the river-level time series, rating curve, and flood-excess volume due to river-bed widening. $\Delta_{Current}$ and Δ_{GRR} signify the water-depth excesses, that is, difference between depth peak discharge and flooding threshold depth h_T, giving an approximation of the necessary flood-wall heights without freeboard, if envisioned [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Comparison of FEVs for various floods

River	Station	Flood date	$V_e(Mm^3)$	$h_T(m)$
Aire	Armley (Leeds, UK)	26/27-12-2015	9.34 ± 1.50	3.9
Calder	Mytholmroyd (UK)	26/27-12-2015	1.65 ± 0.60	4.5
Don	Sheffield Hadfields (UK)	25/26-06-2007	3.0 ± 0.71	2.9
Brague	Biot (France)	3/4-10-2015	0.488 ± 0.311	3.06

ment, one can start to consider whether multiple NBS techniques such as flood-storage reservoirs or flood-plain enhancements are feasible. The River Calder valley is not only distinctly narrow but also quite urbanised, so it is difficult to find substantial flood-storage sites in the Calder valley by enhancing the flood-storage capacity of existing flood plains. Increase in conveyance capacity was studied for the River Brague, where marginal widening of the river bed is feasible. Flood-mitigation assessments are now addressed.

4 | MAIN RESULTS: FLOOD-MITIGATION ASSESSMENTS

Several NBS (and other) approaches are reviewed with regards to their capacity for large-scale flood mitigation; each one is exemplified in hypothetical flood alleviation schemes for the River Calder in the Upper Calder subcatchment in Yorkshire and the River Brague in France (see Figure 2). There have been numerous NFM measures reported—in newspapers, online, by flood-action-group websites, and elsewhere—with either vague or excessive claims of their efficacy towards flood mitigation. NFM is momentarily popular in Europe, so we provide a way to substantiate whether it can actually be beneficial on larger, catchment scales for more extreme flood events—a crucial requirement for integrated catchment flood management. Our FEV analyses contextualise these claims and reveal both pitfalls and merits of different NFM flood-mitigation strategies. It is useful to recall that effectiveness is defined as the comparison of the actual technical capacity of a protection device measured by an indicator (here FEV) with an objective value. Cost-effectiveness then analyses costs to reach a given objective.

4.1 | River Calder Boxing Day 2015 flood

For the River Calder, we consider three different types of NBS separately, using its FEV of $V_e(h_T = 4.5\text{ m}) \approx 1.65$ Mm^3 given in (2) for the 1 : 100-year return period Boxing Day flood, before assessing their contributions in a hypothetical flood-alleviation scheme.

4.1.1 | NFM: flow-attenuation features

NFM using flow-attenuation features such as leaky dams has received much attention in the United Kingdom since the successful collaboration between the Environment Agency (EA) and citizens of

TABLE 2 Areas involved, fraction of total Calder area, flood-storage volume V_t^* and V_t^*/V_e

Name	Area (Mm^2)	Fraction (%)	$V_t^*(m^3)$	$V_t^*/V_e(\%)$
Calder	957	100	–	–
Upper Calder	~ 182	$\frac{182}{957} \approx 19.02$	–	–
Trees	1.03	$\frac{1.03}{957} \approx 0.11$	$\frac{1.03}{182} 12.879 \times 10^6 \approx 72,887$	$\frac{72887}{1.65\times 10^6} \approx 4.42$

Note. Recall from (2) that $V_e = 1.65$ Mm^3.

Pickering (Harrabin, 2016). What is less well-known is that 10% of that "NFM" scheme consists of leaky-woody-debris dams, with 90% of the enhanced storage created behind a large controlled cement bund (Potter, 2016). We therefore introduce the small-scale pilot project of the citizens' action group "Slow-the-Flow-Calderdale," upscaling of which to the River Calder catchment scale we consider later. The pilot consists of creating and maintaining run-off attenuation features and restoring old mill ponds to slow the flow so as to increase water-storage capacity (Bradshaw, 2017). An estimate was made of the (effective) attenuation volumes obtained by these interventions, which included ~120 plate weirs, leaky (small- and large-woody-debris) dams and strategically placed logs as well as restoring plantations on ancient woodland sites. Using two approaches to facilitate estimation, an available (effective) flood-storage volume of $\sim 7,000$ m^3 was foreseen at a project cost of ~£50,000 to £72,000 (Bradshaw, 2017). Here, we have assumed that the aforementioned cumulative volume of $7,000$ m^3 concerns the available flood-storage volume because this distinction was not made in the available information (cf. Bradshaw, 2017 and personal communication with the Calderdale flood-action group). Long-term maintenance is not included within the cited costs. In addition, the building and maintenance in the field will provide and disseminate valuable insights into flood management and biodiversity within the local area. However, the contribution of these NFM measures in the context of preventing or mitigating an extreme flood is minute when compared with the total FEV (2) of the Boxing Day 2015 flood, that is, $V_e(h_T = 4.5\text{m}) \approx 1.65$ Mm^3. Under the assumption that the extreme rainfall is uniform and that the attenuation features function optimally, the cumulative storage would lead to at best a $7,000/(1.65 \times 10^6) = 0.0042$ or 0.42% reduction in FEV.

Furthermore, it remains unclear whether these attenuation features can attain their full capacity in very wet periods, in which most of the required extra capacity may already have been used up by the increased level of sustained rainfall. Justification of the above assumptions requires more field tests and monitoring combined with mathematical and fluid-dynamical modelling, including optimisation of the placement of the leaky dams; for example, of the kind undertaken in Cabaneros et al. (2018). Nonetheless, such estimation of the efficacy of these run-off attenuation features shows that upscaling (to cover a larger fraction of the FEV) to a ten- or hundred-fold increase in flood storage, even for floods a tenth of the size of the Boxing Day 2015 floods, and then involving, say, 1,200–12,000 attenuation features, is required to raise flood-storage contribution to more reasonable flood-mitigation levels of 4.2% or 42%. The costs increase correspondingly to £$[0.5, 0.7]$ M or £$[5, 7]$ M: this calibration/comparison—comprising a sanity check—with real data seems to have been neither recognised nor conducted hitherto.

4.1.2 | Floodwater storage in reservoirs

Both Yorkshire Water (YW) and the EA have started to explore a flood-storage project in which levels in drinkwater reservoirs in the upper catchment of the River Calder will be lowered prior to imminent or during extreme-rainfall events in order to provide floodwater storage[2]. These reservoirs lie mostly upstream of Mytholmroyd, making analysis of the Mytholmroyd case relevant. Both static draw-down and dynamic control of the draw-down in anticipation of extreme rainfall are under investigation at the EA. Static reservoir storage can be achieved by drawing down six reservoirs by 10% in volume. The total volume of floodwater storage in these reservoirs is estimated to be $V_r \approx 0.88$ Mm^3, which is a significant ~53.3% of the River Calder Boxing Day 2015 FEV when compared with the target volume $V_e \approx 1.65$ Mm^3. This estimate of V_r's contribution is again based on the assumption that the extreme rainfall is spatially uniform, such that the reservoirs' capacity can be reached; this was roughly the case for the Boxing Day 2015 flood. Conversely, spatial non-uniformity in the rainfall will change (generally reduce) the storage capacity; it can also increase the capacity when the rainfall is localised near the reservoirs. Summarising, it is clear that flood storage in reservoirs offers significant contributions to flood-mitigation approaches.

4.1.3 | NFM: tree planting and peat restoration

YW recently advertised various flood-mitigation measures, including tree planting and peat restoration, flow-attenuation features, and reservoir usage for floodwater storage (Yorkshire Water, 2014). YW mentions 43 ha of blanket-bog restoration and 60 ha of "environmental improvements such as leaky dams, fascines and wetlands to slow the flow of the water," totalling an area of $A_b = 103$ ha. To make a first estimate of what is attainable by these NFM measures of tree planting and peat restoration on an area of $A_b = 103$ h$a = 1.03$ Mm^2, consider the total catchment area of the River Calder $A_t = 957$ Mm^2. Assuming a best-case scenario in which all water is held back on $A_b = 1.03$ Mm^2, and for uniform rainfall over the catchment, the contribution of these measures is at best (see Table 2) $A_b/A_t = 1.03/957 \approx 0.11\%$ of the *total water volume*, providing an upper bound on the estimated flood mitigation. It is difficult to obtain an estimate of the total volume because it is somewhat ambiguous to define flood duration for a total flood volume. An estimate follows by calculating (using the data in Figure 3) the excess volume for a low (nonflooding) threshold of $h_T = 1.5$ m, thus enforcing that a larger time interval is taken into account and, via (1), yielding an "excess" volume of $V_{et}(h_T = 1.5 \text{ m}) = 12,879$ Mm^3. Hence, by taking the above fraction $A_b/A_t \approx 0.11\%$ thereof, we estimate an available flood-storage volume of $\sim$ $V_t = 0.0011 V_{et} = 13,861$ m^3, about $V_t/V_e = 13,861/(1.65 \times 10^6) \approx 0.84\%$ of the FEV. Given that

[2]Personal communication: Andrew Coen and Simon Byrne (EA).

Mytholmroyd lies further upstream in the River Calder catchment, the relevant area A_t considered should be smaller and concern only the fraction (~20% and thus leading to an adjusted $V_t^* \approx 72,887\ \mathrm{m}^3$) of the total catchment area draining water into Mytholmroyd, cf. the update in Table 2. On the one hand, this would lead to a larger percentage than the 0.84% estimate above; on the other hand, that increase is likely to be offset by the absorption being much less than the assumed 100%. Again, the contribution of this NFM measure is small and difficult to quantify.

4.1.4 | Cost-effectiveness analysis for hypothetical flood-alleviation scheme

A cost-effectiveness analysis for a hypothetical River Calder flood-alleviation scheme is presented, resulting in a novel and graphical illumination, for example, for policy makers. It consists of partially upscaled versions of the NFM measures discussed above.

Consider flood mitigation by flood-attenuation features resulting in an available flood-storage volume of $V_a = 140,000\ \mathrm{m}^3$ at a base cost of £1.44 M for ~2,400 attenuation features, spread out relatively evenly over the upper catchment; a deliberately chosen 20-fold increase of the Slow-the-Flow-Calderdale case discussed above, offering a $V_a/V_e = 140,000/(1.65 \times 10^6) = 0.0848 = 8.48\%$ FEV reduction. Leaky-woody-debris dams degrade over time and so, to illustrate our protocol, we assume features have an average life span of 25 years. Over 50 years, these need to be constructed twice, leading to twice the base costs, that is, a total of £2.88M, excluding maintenance. These 2,400 features should be replaced using a smart, staggered-replacement scheme to reduce serial failure of dams at certain times, which can lead to devastating flood-wave damage, cf. Cabaneros et al. (2018): this is an interesting optimisation problem not considered here. Over 50 years, $2 \times 2,400/50 = 96$ features p.a. require replacement. We employ one person at ~£50 k p.a. to carry out maintenance, resulting in £2.5 M employment costs over 50 years (again, as illustration), yielding a total cost of £(2.88+2.5) M =£5.38 M over 50 years, £0.634 M per 1% of flood protection (note that we ignored inflation and rising costs of living). It is neither clear whether full available flood-storage volume is reached nor the extent to which this capacity is reached under varying spatial rainfall distributions. Hence, we introduce this uncertainty via an ad hoc sliding scale of coverage between 50% and 100% of the above capacity. Final ranges for the available flood-storage volume, its FEV fraction, and costs therefore become $[0.07, 0.14]\ \mathrm{Mm}^3$ or $[4.24, 8.48]\%$ at a cost £5.38 M or £[0.634,1.268] M per 1% of flood mitigation. Using a similar sliding-scale approach, the available flood storage offered by the reservoirs is $V_r = [0.44, 0.88]\ \mathrm{Mm}^3$, yielding a coverage of $V_r/V_e = [0.44, 0.88]/1.65 = [0.2667, 0.5333] = [27, 53]\%$ at an estimated cost of £30M, including £5 M operational costs over 50 years, which yields £[0.5625, 1.1251] M per 1% of flood mitigation.

In Leeds' flood-alleviation scheme (Leeds City Council, 2018), it is proposed to increase tree coverage in the River Aire valley from 8% to 15%. We therefore assume another type of NFM by increasing the area of tree and peat coverage to 6% instead of the 0.84% estimated above. Again, using a sliding-scale approach, this yields an increase of flood-storage volume by $[0.0495, 0.099]\ \mathrm{Mm}^3$, so $[3, 6]\%$ at an estimated cost of £6 M including maintenance costs over 50 years, giving a window of £[1, 2] M per 1% of flood mitigation.

We assume that the above NFM measures are distributed uniformly across the catchment section influencing river flow in Mytholmroyd. Without further information on the spatial and temporal distributions of rainfall during extreme rainfall and flood events, we assume that the flood mitigation offered varies linearly between the most adverse case with minimum 33.90% flood-mitigation coverage offered by combined measures and maximum 67.81% coverage with mean 50.86% at a cost of £41.38 M for £41.38/50.86 = £0.8136 M per 1% of flood mitigation. The above cost-effectiveness analysis is visualised in Figure 7. It becomes apparent that reservoir usage (blue shaded area in Figure 7) is the largest and most cost-effective fraction of FEV. Increased tree coverage (green area in Figure 7), a small but not insignificant fraction, offers less value for money. Major upscaling of flood-attenuation features (brown area in Figure 7) has a considerable cost-effective impact. Unmitigated FEV parts can be covered by other mitigation measures: by building higher flood-defence walls than currently in place or further increasing the reservoir volumes via dynamic control (Breckpot, 2013; Breckpot et al., 2013; Vermuyten et al., 2017). However, optimisation of the draw-down of reservoirs would involve cost functions with the opposite demands of drinkwater maximisation, volume min-

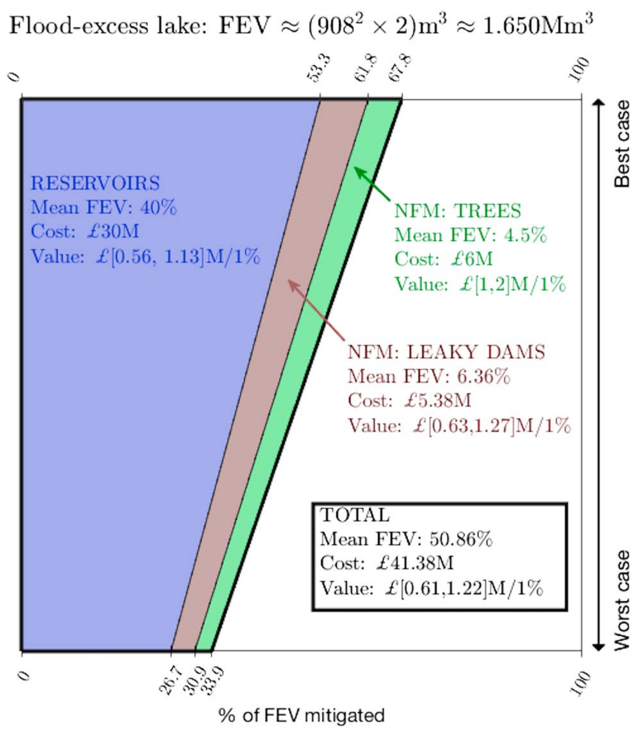

FIGURE 7 Graphical overview of flood-excess volume (FEV) fraction captured by three flood-mitigation measures and associated costs for the River Calder at Mytholmroyd. FEV ≈ 1.65 Mm^3 is represented as a 2 m-deep square lake of side-length 908 m, illustrating the flood's magnitude, partitioned here by each measure. Overall flood mitigation ranges from 33.90% to 67.81% at a cost of £41.38 M. The mean of each measure is represented by corresponding quadrilateral areas, partitioning the overall square-lake area with the same FEV-capacity requiring mitigation. Sloping lines reflect the sliding scale between quoted ranges, owing to storage-capacity uncertainty

TABLE 3 Size, unit, and total costs of protection measures on the Brague

Measure	Size	Land acquisition	Unit costs Investment	Maintenance	Total cost[a]
Retention basins	120,000 m^3	Neglected[b]	100 €/m^3	0.3 €/m^3/year	13.8 M€
Flood walls	2 banks × 1.3 m × 2,400 m	Neglected[c]	1,040 €/m^2	4.6 €/m^2/year	7.9 M€
GRR	5 m × 2,400 m	152 €/m^2	120 €/m^2	0.8 €/m^2/year	3.7 M€

[a]Total costs = (Size) × (Investment + Land acquisition + Maintenance × 50 years). [b]Built-in natural areas with low land prices compared with building costs. [c]Concrete walls have sufficiently small footprints not to require land acquisition.

imisation, dam safety, and controlled water release with minimal flood, erosion, and environmental damage.

Alternatively, more attenuation features can be built, or more trees and peat restoration in combination with controlled ponding. Co-benefits of tree planting and peat coverage can be taken into account in cost assessments, such as carbon sequestration and recreational value (Denjean et al., 2017), but all these measures and decisions demand a clear quantification, especially given the weak evidence for the effect of tree coverage on channel discharge (Carrick et al., 2018). The above analysis and in particular its graphical presentation in Figure 7 suggests that our FEV-based protocol can aid in more quantifiable and rational decision making.

4.2 | River Brague 2015 flood

The following flood-mitigation analysis for the River Brague is exploratory and distinct from the actual Brague protection scheme to date under study. We highlight a long-term plan to protect the Brague floodplain. Investments and consequences on land use along the river corridor are sufficiently high to warrant time to implement any plan. We pursue this analysis because discussions with various stakeholders highlight that orders of magnitude of discharge, volume, water depth, effectiveness, and costs of protection measures are generally unknown, resulting in less-informed debates on relevant protection schemes.

Economic[3] data were gathered from local past works, land-acquisition operations, and existing literature (Aerts, 2018; CASA, 2013; Igigabel et al., 2014; Langumier et al., 2014) to instigate quantification of cost-effectiveness analyses (Table 3). In the absence of data, this analysis cannot yet be done on Biot's downstream section threatening Antibes. GRR seems however a good option downstream too since riparian areas are either natural or abandoned following business closures due to excessive flood risks.

Figure 6 depicts the FEV analysis of the Brague case in (a) the current bed configuration and (b) a GRR strategy. The current Brague river width is typically 20 m. The scenario models a small widening of a 5-m-width increase of the section at a height of 1.5m above the bed-base level (cf. Figure 5), which raises the bed-discharge capacity from 135 to 157 m^3/s for the same water depth h_T before flooding. The remaining FEV decreases from V_e = 0.488 Mm^3 to $V_{e,GRR}$ = 0.352 Mm^3. The FEV-effectiveness of this measure is thus at least 0.136 Mm^3. Raising flood walls may enhance this measure with a better effectiveness than in current bed configurations: raising of equivalent heights will have a higher hydraulic capacity for wider

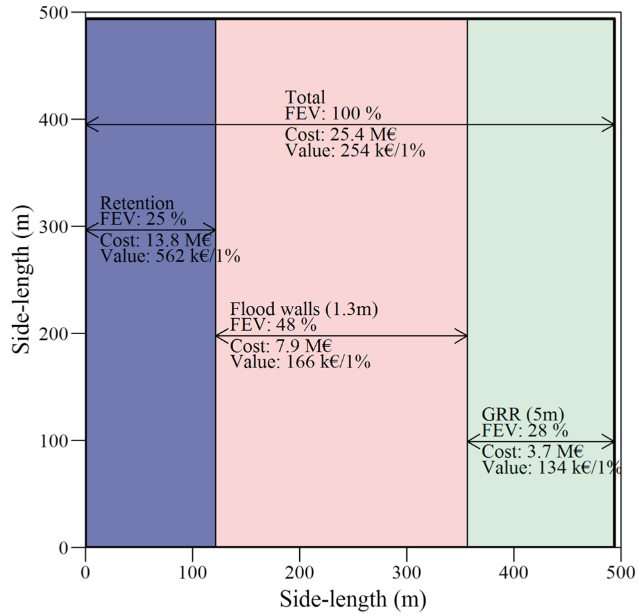

FIGURE 8 Square-lake representation of Brague protection scheme. The flood-excess volume (FEV) V_e = 0.488 Mm^3 is represented by a 2-m-deep square lake of side 494m. Excess volume is managed by three protection measures. Darker colours represent higher costs per measure per FEV percentage. More than half of the 25.4 M€ scheme is related to retention measures even though they manage only 25% of the problem. Giving-room-to-the-river (GRR) is most cost-effective

beds as a consequence of steeper stage-discharge relationships (cf. Figure 6, top-left).

Participative workshops organised by the authors in March, June, and December 2018 have shown that local citizens ask for more retention measures: for example, the Vallon des Combes, a Brague tributary, has been equipped with a 12,000 m^3 retention basin for a catchment twenty times smaller than the Brague's. In addition to width increase, we also added a tenfold-larger than currently implemented, i.e., a 120,000 m^3 retention measure to the protection scheme. It comprises a FEV fraction of 0.12/0.488 ≈ 25%. The remaining FEV, managed neither by retention nor by GRR, is dealt with by flood walls. The flood-wall height was computed by the difference between the maximum water depth in the wider river (cf. dotted grey line in Figure 6, bottom-left) and h_T, plus an additional 0.5-m freeboard.

Figure 8 summarises results of the Brague cost-effectiveness analysis. The FEV of 0.488 Mm^3 is represented by a 2 m-deep square lake of side 494 m though, considering the hilly topography of the Brague catchment, one can hardly imagine where such a retention area could be constructed. Hence, costs of retention measures in the catchment are high. A partial yet expensive retention is nonethe-

[3]Note that, for currency conversion, €1=£0.86 (as of April 2019).

less possible. The cost of managing 1% FEV is respectively three and four times more for retention basins (562 k€/1% FEV) than for flood walls (166 k€/1% FEV) and GRR (134 k€/% FEV). Figure 8 provides a straightforward visualisation of costs and cost-effectiveness of a given protection scheme: with it, the layperson can readily test several options with varying retention volume and width increase to predict how the economic balance will change. Both the magnitude of the flood problem (exemplified by the side length of the 2 m-deep lake) and costs and effectiveness of measures are displayed in unison, thereby admitting easy and rapid interpretation by stakeholders.

5 | SUMMARY AND DISCUSSION

A protocol has been presented for assessing and comparing the efficacy of several proposed flood-mitigation NBS measures and the controlled draw-down of water levels in drinkwater reservoirs prior to extreme-rainfall events. NBS examples included flood-attenuation features such as leaky dams, river widening, tree planting, and peat restoration, the last two of which are aimed at increasing water retention after rainfall. FEV was revisited and promoted in a novel cost-effectiveness analysis for two cases: (a) the Boxing Day 2015 flood of the River Calder (river-gauge data at Mytholmroyd, United Kingdom) and (b) the October 2015 flood of the River Braque (river-gauge data at Biot, Alpes Maritimes, France).

For the design of flood protection, the following question was addressed: what fraction of the FEV is reduced by a particular flood-mitigation measure? To answer this, FEV was expressed as the equivalent capacity of a 2-m-deep (human-scale) square flood-excess lake. Flood-mitigation measures were then visualised clearly as rectangular or quadrilateral subsections of this square flood-excess lake. Costs of each flood-mitigation measure were presented in terms of this square lake, augmented by arrows annotated with quantifying information alongside the respective fraction of each flood-mitigation measure. Our analysis therefore leads to a digestible dissemination of flood-alleviation plans for policy makers, the public and flood practitioners. FEV has been used in a novel context to analyse various actual NFM measures, explored in catchments of the River Calder and River Brague, as proposed by stakeholders. In an atmosphere of increasingly seeking the best combination of environmental and technical effectiveness for flood-risk reduction, our approach analyses and demonstrates objectively the physical effectiveness of measures that can help stakeholders make relevant decision choices based on both technical and environmental criteria. Notably, the present focus has been on technical cost-effectiveness: it has provided a quantitative and objective estimation of physical capacities of different flood-mitigation strategies. Although such an estimation is an essential part in decision making, in real contexts other criteria have to be addressed, including environmental impacts and social acceptance.

Disappointing may be that the NFM measures undertaken in the River Calder catchment to date will contribute only a fraction (about 1% or less) towards the FEV required to mitigate against an extreme flood with a 1 : 100-year return period. Upscaling of tree planting is difficult: the flood-mitigation achieved risks facing not only much uncertainty but also requires vast and suitable (i.e., good for absorbing and holding water) areas to be covered by trees. Despite its popularity in the United Kingdom and media, flood mitigation by NFM is prone to an apparently undervalued scalability problem. Although NFM can often reduce flooding locally, for low return-period events, it is much more difficult to scale up NFM as a flood-mitigation measure for large-scale and extreme floods (cf. Lane, 2017; Salazar et al., 2012). The benefit of using our FEV analysis is that it quantifies in an easy-to-understand way this (lack of) scalability and potential (or lack thereof) for upscaling. Three flood-mitigation measures are highlighted in that they account for major fractions of FEVs in the cases studied.

- Major upscaling of flood-attenuation features, such as leaky dams, can have a significant and cost-effective impact provided long-term maintenance costs are taken into account. Educated guesses were made for the latter maintenance costs and showed that a robust flood-mitigation protocol can be established.
- Draw-down and control of drinkwater reservoirs for flood mitigation were shown to have great flood-mitigation potential, for the River Calder catchment.
- River-bed widening led to a major and cost-effective reduction of the FEV, thereby lowering the need for high flood-defence walls. Whereas the flood-attenuation and tree-planting NFM schemes considered for the River Calder have less potential in the River Brague catchment, river-bed widening seems to be an underexplored flood-mitigation measure in the Calder catchment.

Across all river catchments, emphasis has been placed on the errors inherent in calculating FEVs, ranging from ~36% for the River Calder to 65% for the River Brague; it stresses the inherent uncertainty in any flood-mitigation planning. However, FEV offers a means of realistically incorporating and quantifying the intrinsic errors into the protocol, over and above other approaches.

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ORCID

Onno Bokhove https://orcid.org/0000-0002-5681-4252
Mark A. Kelmanson https://orcid.org/0000-0001-9676-052X
Guillaume Piton https://orcid.org/0000-0002-0124-0909
Jean-Marc Tacnet https://orcid.org/0000-0003-4731-5440

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