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Participatory modelling for stakeholder involvement in the development of flood risk management intervention options

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ABSTRACT

Advancing stakeholder participation beyond consultation offers a range of benefits for local flood risk management, particularly as responsibilities are increasingly devolved to local levels. This paper details the design and implementation of a participatory approach to identify intervention options for managing local flood risk. Within this approach, Bayesian networks were used to generate a conceptual model of the local flood risk system, with a particular focus on how different interventions might achieve each of nine participant objectives. The model was co-constructed by flood risk experts and local stakeholders. The study employs a novel evaluative framework, examining both the process and its outcomes (short-term substantive and longer-term social benefits). It concludes that participatory modelling techniques can facilitate the identification of intervention options by a wide range of stakeholders, and prioritise a subset for further investigation. They can help support a broader move towards active stakeholder participation in local flood risk management.

Software availability

Netica (CoGF) 4.16 for Windows ©1992–2015. Norsys Software Corporation, 3512 West 23rd Avenue, Vancouver, BC, CANADA, V6S 1K5. Available online from http://www.norsys.com/netica Cost US$285.00(academic)/US$585.00(commercial) (both include technical support and updates for one year). Free demo version available for download at above website (full-featured but limited model size supported).

1. Introduction

The identification of intervention options is a key component of a local flood risk management (FRM) decision-making process. Considerable national and/or regional variation exists in how it is conducted (*cf.* EA, 2010), but at a high-level it can be summarised into six, generic steps (Fig. 1): a) problem definition; b) objective setting; c) benchmark development and setting; d) intervention option scoping and identification; e) intervention option appraisal and; f) intervention option recommendation/selection.

Feedback and iteration is usually employed to help inform and refine options appraisal (steps d–e). However, options identification (steps a–d) is structured more sequentially (although a planning cycle in which objectives and benchmarks are reviewed is commonly included). The sequential structuring of options identification steps means the framing of a local flood risk problem is particularly critical because it constrains the set of FRM objectives that drive the remainder of the process. Incomplete or inaccurate framing may produce poorly formulated objectives which, in turn, may result in incomplete or inappropriate identification of options for appraisal. Thus, the specific local contexts (both physical and socio-economic) that frame a local flood risk problem must be fully understood and explicitly represented within local FRM decision-making processes (Johnston and Soulsby, 2006; Prell et al., 2007). There is, therefore, a strong imperative for FRM practitioners to include the elicitation and integration of situated, stakeholder knowledge (Wynne, 1996; Evans and Plows, 2007) within the options identification steps of local FRM decision-making (RELU, 2010; Haughton et al., 2015).

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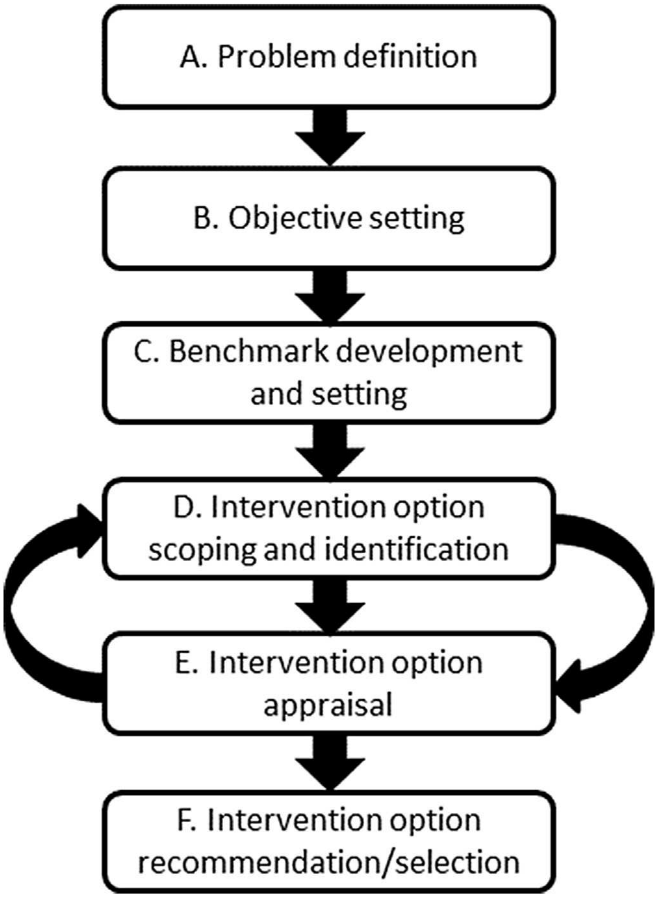

Fig. 1. Generic steps in flood risk decision-making.

In response, formal planning for stakeholder engagement has become a requirement in many FRM options identification and appraisal policies (e.g. USACE, 2000, 2005; EA, 2005, 2006, 2010; DEFRA, 2011) and stakeholders are increasingly seen as full partners rather than consultees in FRM decision-making process (White et al., 2010). However, guidance for practitioners on how stakeholder knowledge can and should be integrated into local FRM options identification, and the benefits that it can deliver, is underdeveloped. Considerable uncertainty about the methods and tools that can be used to engage local stakeholders exists, resulting in wide variation in the nature and scale of engagement across different local FRM projects (e.g. AECOM, 2012; NCC, 2013). The objective of this paper is to improve the guidance that is available by exemplifying how a participatory modelling approach (*cf.* Greenland and Brumback, 2002; Voinov and Bousquet, 2010), coupled with a simple Bayesian network model (BNM), can help to support enhanced options identification in local FRM contexts. The approach taken is particularly novel in the context of FRM in the respect that participants were involved in all stages of model development. In this respect, it represents a considerable departure from previous attempts at participatory flood risk modelling (e.g. Lane et al., 2011) where models have been informed and directed by participation but developed by expert modellers.

The remainder of the paper is structured as follows. Section 2 briefly outlines the principal arguments for and against the adoption of stakeholder participation and participatory modelling in local FRM decision-making. Section 3 presents a case study in which participatory modelling is used to support a local FRM options identification process. The principles and goals of the approach, along with the three-stage structure by which it was organised, are outlined. The methodology is presented in Sections 4 and 5. Details of the stakeholder analysis methodology employed to identify participants, and to inform the local FRM objectives, are provided in Section 4. The participatory modelling methodology (including the approach, tools used and the co-development process) is described in Section 5. In Section 6 the local FRM intervention options identified by the participatory model are presented. Section 7 provides a comprehensive evaluation of the participatory modelling process and its outcomes. Finally, lessons for using participatory modelling in local FRM are synthesised in Section 8.

2. Stakeholder participation in flood risk decision-making

The participation of stakeholders throughout environmental decision-making (including FRM) is an established principle, underpinned by a comprehensive statutory framework (e.g. ICWE, 1992; UNEP, 1992; UNECE, 1998; EC, 2000, 2003, 2007). Expert knowledge *per se* is increasingly seen as insufficient for informing decisions concerned with specific local contexts (e.g. Wynne, 1992, 1993; Robbins, 2000; Cinderby and Forrester, 2005; Eden et al., 2006; Douglas et al., 2010). Instead, it is recognised that in many decision-making processes the adoption of a participatory paradigm (Brown and Damery, 2002; Reed, 2008; Barreteau et al., 2010) is needed so that those possessing both certified expertise and situated knowledge (which need not be mutually exclusive) can be

Fig. 2. Hebden Bridge town centre (left) and surrounding landscape (right).

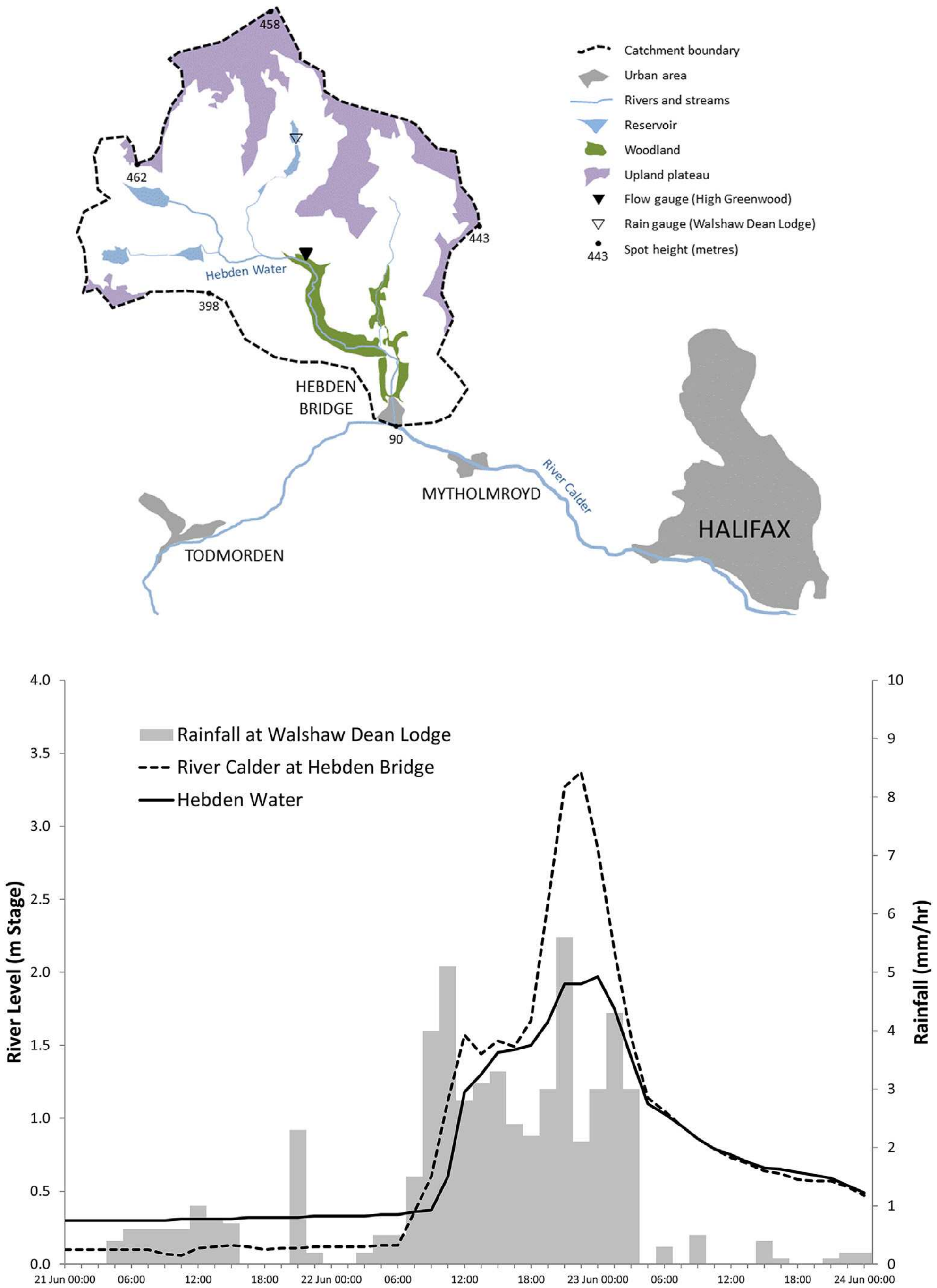

Fig. 3. Hebden Water catchment with inset UK locator map (above) and hydrograph from 21 to 24 June 2012 (below). Redrawn from the Upper Calder Flood Hydrology Report (EA, 2012).

effectively engaged in the co-production of the knowledge necessary to inform decisions (Callon, 1999).

Three benefits of a participatory paradigm are regularly cited (see Fiorino, 1990; Stirling, 2006; Chilvers, 2008a,b; 2010): 1) normative benefits that enhance citizen empowerment, equity and social justice in decisions and the evidence that underpins them (e.g. Renn et al., 1995; Bohmann, 1996); 2) instrumental benefits that enhance the legitimacy of evidence and decisions, and the trust that is afforded to them (e.g. Gaddis et al., 2010; Voinov and Bosquet, 2010) and; 3) substantive benefits that enhance the quality of the evidence underpinning the decisions that are ultimately made (e.g. Stirling, 1998). In FRM, the findings from several recent participatory studies appear to confirm this by reporting a range of normative and instrumental benefits (Landström et al., 2011, Lane et al., 2011; Odoni and Lane, 2010; Ryedale Flood Research Group, 2008; Whatmore, 2013).

However, the notion that participatory approaches and the engagement of stakeholders alongside certified experts will inevitably lead to better decision-making should be avoided. The value of stakeholder ‘expertise’ remains contested within social science generally (e.g. Jasanoff, 2003; Collins and Evans, 2008; Tsouvalis and Waterton, 2012) and FRM practice in particular (e.g. Haughton et al., 2015). Previous studies highlight important challenges related to the biases of those participating in the

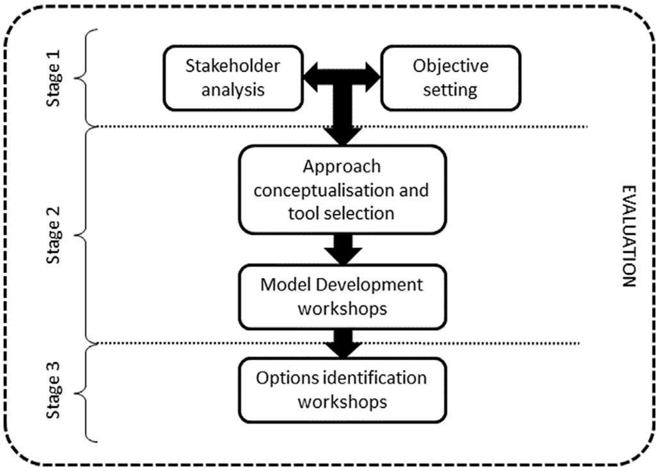

Fig. 4. The structure of the participatory modelling process used in Hebden Bridge.

decision-making process, and the effectiveness of the approaches and tools used to facilitate participation and represent the knowledge that is co-produced (*cf.* Irwin, 1995; Wynne, 1992, 1993). In FRM, Haughton et al. (2015) caution against a 'romanticised view' that local stakeholders are always necessary and beneficial for the creation and stewardship of situated flood risk knowledge. Instead, the case for participation should be supported by comprehensive evaluation of the extent to which participatory approaches deliver beneficial outcomes for local FRM decision-making processes. In this regard, the limited number of published studies providing such evaluation is a significant constraint on the guidance that is available to FRM practitioners, and is something that this study helps to redress.

3. The participatory modelling case study

The remainder of this paper focusses on the development and evaluation of a participatory local flood risk intervention model for Hebden Bridge. Hebden Bridge is a small market town (population 4500) situated roughly eight miles west of Halifax, West Yorkshire, UK (Fig. 2). The town centre is located on a narrow floodplain located at the confluence of the River Calder (catchment size 957 km^2, mean discharge ~4.1 m^3 s^{-1}) and Hebden Water (catchment size 59 km^2, long-term mean discharge ~0.7 m^3 s^{-1}), surrounded by a steep sided valley (Figs. 2 and 3). Both the River Calder and Hebden Water drain upland catchments where high-intensity, convective rainfall events occur. The catchment physiography results in a flashy hydrological regime; and if high discharge in Hebden Water and the River Calder coincide, flow in Hebden Water backs up, flooding the town centre. In addition, localised, convective rainfall contributes to incidences of pluvial flooding. In summer 2012 Hebden Bridge experienced two major instances of flooding; the first being primarily fluvial and the second pluvial. On the 22nd June, discharge in the River Calder peaked at 190 m^3 s^{-1} (~1:70 year flood) resulting in a back-up of water into Hebden Bridge town centre, which peaked at 1.97 m stage (Fig. 3) and flooded 219 properties (CMBC, 2013a). A second event on 9th July was a result of intense localised rainfall from a short-lived storm cell, flooding around 100 properties, including several affected by the June event (CMBC, 2013b).

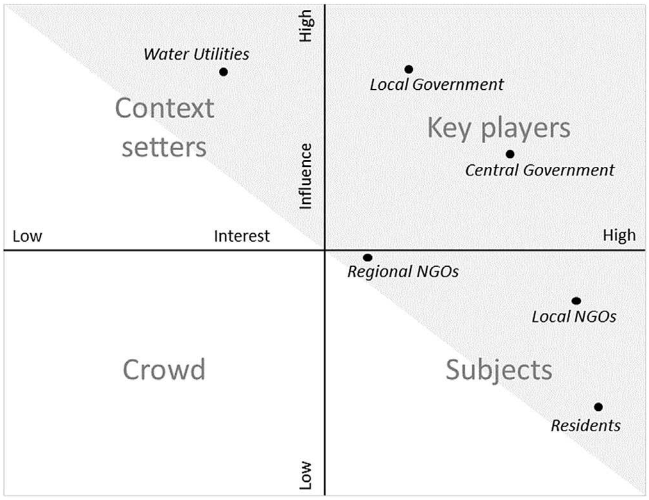

Fig. 5. Stakeholder mapping in Hebden Bridge.

Despite these events, and further flooding in December 2015, Hebden Bridge remains largely undefended. Topographical constraints and the challenges of trying to combat both fluvial and pluvial flooding mean that is has been difficult to identify appropriate and affordable flood interventions for the town. The high capital cost of hard-engineered schemes and the need to raise funding through local partnerships (*cf.* Thaler and Priest, 2014) have been significant barriers. Moreover, controversy exists around hard-engineered interventions over concerns that they could endanger the town's attractive and historic urban setting which underpins much of its local economy (Fig. 2). Following the 2012 floods, it was recognised that the reduction of flood risk in Hebden Bridge may need to be affected through interventions designed to enhance the town's flood resilience, rather than to reduce the probability and magnitude of flooding. This prompted a collaborative project between the Environment Agency for England and Wales, Calderdale Metropolitan Borough Council (the Lead Local Flood Authority) and researchers at the University of Nottingham.

The project aimed to design and test a new approach to FRM options identification that structured, formalised and integrated the situated knowledge of local stakeholders and expert knowledge of practitioners (hereafter termed 'participants') in a process of co-production. The objective was to develop a participatory model of local flood risk interventions from which novel options, perceived to be suited to the specific local physiographic and socio-economic context of Hebden Bridge, could be identified. These could then be advanced for formal appraisal. In addition, the project also sought to deliver an evaluation of the extent to which the process of developing a participatory flood risk intervention model could deliver normative and instrumental benefits required to promote social learning amongst the participants.

Three principles governed the project:

Principle 1. The participatory model must be the combined product of the knowledge of those who participated in its construction;

Principle 2. The transparency and accessibility of the modelling methods used must be sufficient to enable *all* participants (including those with low levels of numerical and/or technical skill) to be fully engaged in the model development process and to be capable of continuing to use the resultant model;

Principle 3. The participatory modelling process should maximise the quality, rather than the volume, of participatory elements in order to maintain the engagement of the participants (the majority of whom were volunteers giving up their free time).

The participatory modelling process had three goals:

Table 1
Catchment objectives.

Objective	Description
1	To reduce surface runoff
2	To store and slowly release excess stormwater from appropriate areas
3	To create more space for water in the river
4	To improve land management
5	To manage the flow of surface water
6	To adopt water-sensitive approaches to construction and development, which offer multiple benefits beyond those of reducing flood risk
7	To understand the current role of the reservoirs
8	To raise awareness of what residents can do to prepare for flooding
9	To raise awareness of what residents can do to recover from flooding

Table 2
Participating stakeholder organisations/groups.

Organisation/group	Description	Participants
Environment Agency	National regulator	3
Calderdale Metropolitan Borough Council	Local government and lead local flood authority	11
Yorkshire Water	Water utility	1
National Trust	Landowner	1
Hebden Bridge Partnership	Local non-governmental organisation (community, recreation and tourism)	2
Business Owners Association	Local non-governmental organisation (business, trade and tourism)	2
Calder and Colne Rivers Trust	Local non-governmental organisation (recreational and ecological stewardship)	2
Treesponsibility	Local non-governmental organisation (land management)	3
Pennine Prospects	Regional non-governmental organisation (upland management)	1
Moors for the Future	Regional non-governmental organisation (upland management)	2
National Flood Forum	National non-governmental organisation (flooding)	1
University of Leeds	Research institution	2
University of Nottingham	Research institution and facilitator	4
Local residents	No affiliation	5

Table 3
Variables in a cause-effect model of local flood risk interventions (modified after Cain, 2001).

Variable type	Definition	Example
Objective	A variable describing an **outcome** that may be affected by interventions within the physical/socio-economic systems.	Flood probability, property level resilience, community awareness, response planning.
Intervention	A variable encoding an **action** that could be taken to help achieve an objective.	Property-level protection, drain maintenance, education programme, flood warden scheme.
Implementation factor	A variable whose state determines whether an intervention can be successfully **implemented**.	Funding, the planning system, land availability, environmental protection, visual impact.
Control factor	A variable that exerts **controls** the flood risk system that cannot be easily manipulated or modified.	Precipitation intensity, topography, storm water system, pre-existing flood plain development.
Intermediate factor	A variable between an intervention and objective needed to **explain** the cause-effect.	Channel capacity, infiltration rate, demographic composition.

1. To establish a set of local flood risk management objectives that interventions should address (i.e. step b in the options identification and appraisal process) (see Fig. 1);
2. To produce a formal model of the participants' perceptions and understanding of local flood risk cause and effect and the impact that alternative interventions might have on this;
3. To explore the relative extent to which alternative intervention options might be able to address the objectives, and to inform a shortlisting of interventions that the participants identified as warranting further appraisal (i.e. step d in the options identification and appraisal process).

In order to achieve these goals, the participatory modelling process was structured into three key stages (Fig. 4):

Stage 1. A coupled stakeholder-led determination of a set of objectives for reducing flood risk in Hebden Bridge and analysis of stakeholders with the situated knowledge necessary to inform the modelling process (see Section 4);

Stage 2. The co-development of a BNM of local flood risk interventions representing participants' shared understanding of the local flood risk system and the interactions between interventions and objectives within the system (see Section 5);

Stage 3. The application of the model to explore and assess the impact that applying different interventions (and combinations thereof) had on the objectives (see Section 6).

Importantly, it was recognised from the outset that the scope of the interventions considered should not be constrained to physical components of the flood risk system (i.e. management of flood sources and pathways), but should include aspects by which the impact on receptors might be managed (e.g. social actions and blue-green infrastructure). It is also important to note that neither the participatory modelling process, nor the model it produced, were conceived as a replacement for the hydraulic, hydrologic, economic and social models that would be needed to inform comprehensive options appraisal (*cf.* Evans et al., 2002; Sayers and Meadowcroft, 2005).

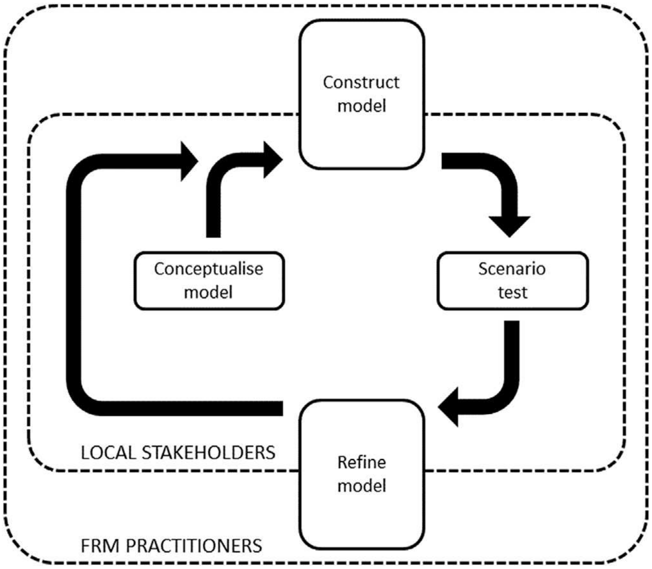

Fig. 6. Mediated modelling approach (after Van den Belt, 2004).

4. Stakeholder analysis and objective setting (Stage 1)

The outcomes of a participatory modelling process will inevitably reflect the knowledge and understanding of the participants. A systematic method for analysing stakeholders, and identifying those with the breadth and diversity of situated knowledge required to meet the goals of the participatory process, is essential (Mitchell et al., 1997; Bryson, 2004; Reed et al., 2009). In this project, there was a lack of pre-existing relationships with stakeholder groups (e.g. local flood action group or residents/business owner campaign groups). This made it was necessary for the researchers to identify and traverse local networks of stakeholders, so that the FRM objectives for Hebden Bridge could be elicited and project participants could be identified. To this end, an iterative, top-down stakeholder identification methodology was used (Dougill et al., 2006; Prell et al., 2008), which is sometimes referred to as 'snowballing' or 'referral sampling' (Harrison and Qureshi, 2000; Hair et al., 2000). To minimise sampling bias and the marginalisation of stakeholder groups (Ananda and Herath, 2003; Reed et al., 2009), a simple stakeholder classification of key players, context setters, subjects and the crowd was adopted (*cf.* Eden and Ackermann, 1998; De Lopez, 2001). This enabled the project team to structure the range of stakeholders that were identified according to the diversity of their local flood risk interest, expertise and experience (Fig. 5). Stakeholders that mapped to the quadrants overlapping the high-interest, high-influence regions of the classification were invited to participate in the project as an initiation group.

The initiation group was interviewed, with the transcripts ($n = 10$) analysed in order to extract two key sets of information: i) a set of FRM objectives for Hebden Bridge (Table 1); and ii) a list of potential new stakeholders. Utilising a referral-based stakeholder analysis was successful in maximising the efficiency of stakeholder identification. It resulted in a final participant group comprising 40 stakeholders representing 14 separate organisations/groups (Table 2). They represented a wide range of situated knowledge and expertise (*cf.* Collins and Evans, 2008) including certified experts from context setting and key player organisations, and uncertified experts from local community and campaigning groups.

5. Participatory model development: conceptualisation, approach, tools and activities (Stage 2)

5.1. Conceptualisation of the local flood risk system

A major challenge for any participatory modelling project in which the goal is for participants to co-develop the model is the selection of the modelling approach and tool. To maximise their legitimacy they should offer all participants equality of access and use. However, this can be difficult where the diversity of the participants is high and includes those with high levels of technical and numerical expertise and those with little. This was the case in Hebden Bridge where some participants had substantial expertise in flood risk modelling (e.g. participants from the Environment Agency) while others had none and little confidence in quantitative modelling methods. Therefore, a highly conceptual modelling methodology was devised that abstracted the local flood risk system to a set of cause-effect relationships between flood risk objectives, controlling factors, potential interventions, implementation factors and intermediate factor variables (Table 3). This conceptualisation paralleled the vernacular used by many local stakeholders to express their understanding of the flood risk system. This meant that the model variables could be elicited directly from participants through directed, group discussion with no assumed level of technical competence. It also facilitated the structuring of knowledge using simple probabilistic representations, formalised within a simple Bayesian network model (BNM) that offered both quantitative rigour and ease of understanding for all participants (see Section 5.2).

5.2. Participatory modelling approach and modelling tool

Co-development of the model was structured around four model building tasks:

Task 1. Identification of the variables that must be represented in the participatory model;

Task 2. Structuring of the causal pathways between them;

Task 3. Formalisation of each variable as a state variable – i.e. that can hold a mathematical description of its state at any given time;

Task 4. Formalisation of the mathematical, cause/effect relations that are transmitted along the causal pathways and influence the states of each variable.

In participatory modelling, formalised approaches (Voinov and Bousquet, 2010) direct the eliciting and structuring of participants' knowledge (Tasks 1 and 2). While a number of different participatory modelling approaches have been proposed (e.g. Vennix, 1996; Barrateau et al., 2010; Palmer et al., 2013), this project employed an adaptation of the mediated modelling approach (Van den Belt, 2004) (Fig. 6). Mediated modelling was considered particularly appropriate for Hebden Bridge because it gives salience to the process of interfacing participants with different levels of expertise so that models can be co-developed that are readily understood and accepted by all participants.

To complete Tasks 3 and 4, quantitative or semi-quantitative tools are needed to provide a mathematical formalisation of model variables (Table 3) and the propagation of cause and effect between them. In Hebden Bridge it was decided to use a BNM (Pearl, 1985, 1988; Varis, 1995) due to the relatively simple and intuitive way in which it supports conceptual modelling of environmental systems, and the flexibility with which different knowledge types can be represented within it (for a review see Aguilera et al., 2011).

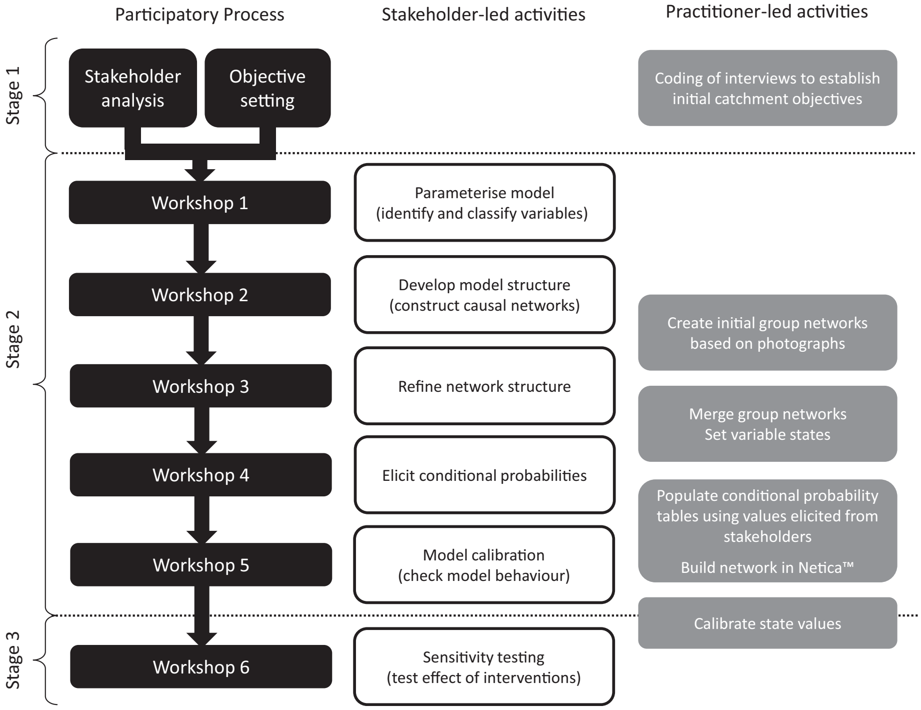

Fig. 7. Participatory approach adopted in Hebden Bridge.

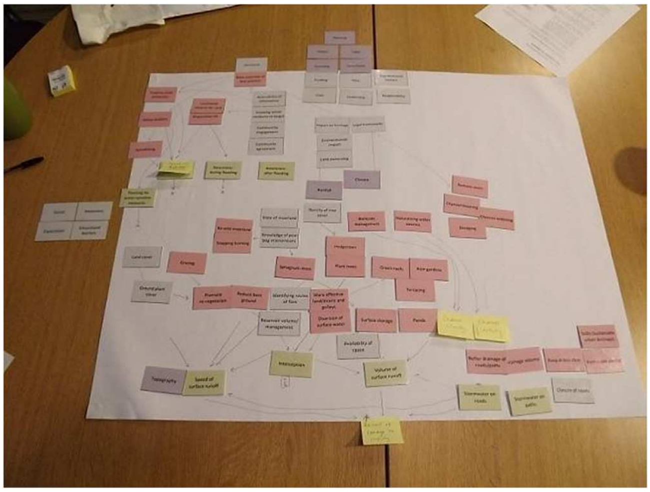

Fig. 8. An example 'network of causality' produced by the participants during workshop 2.

A BNM combines Bayesian probability theory and notions of conditional independence. It is a directed acyclic graph (Greenland and Brumback, 2002) whose edges are the causal or inferential links between uncertain variables that have a number of discrete states (Neil et al., 2000). Conditional probability tables (CPTs) associated with each variable represent the uncertain relationship between the states of each variable and its parents (Hanneman, 1988). Examples of the use of BNMs to model environmental systems are numerous (e.g. fisheries management (Kuikka et al., 1999; Borsuk et al., 2001; Little et al., 2004), catchment management (Ames et al., 2005) and water resource use (Varis and Kuikka, 1997; Batchelor and Cain, 1999)), and they have been shown to be an effective tool for engaging stakeholders so that gaps in evidence bases can be addressed (Varis and Kuikka, 1997; Henriksen et al., 2007). Studies highlight several benefits of BNMs including the ability to structure and combine knowledge from multiple sources (Marcot et al., 2001; Ticehurst et al., 2007); represent a system conceptually without requiring the explicit representation of all system processes (Borsuk et al., 2004); and easily update a model as new data or knowledge becomes available (Castelletti and Soncini-Sessa, 2006; Ticehurst et al., 2007).

In the majority of examples of BNMs reported in the literature (e.g. Smith et al., 2007, 2012; Murray and van Klinken, 2012; Murray et al., 2014), the objective of the Bayesian network model is the delivery of substantive outcomes. Most commonly, this centres on providing enhanced prediction through a model development process that is informed by experts possessing moderate levels of technical and numerical expertise. However, in this study broader outcomes from the modelling process were sought; including the delivery of normative and instrumental benefits alongside substantive ones. To this end, studies that have shown BNMs to be capable of facilitating participation-led studies are of particular relevance (*cf.* Marcot et al., 2001; Castelletti and Soncini-Sessa, 2006; Henriksen et al., 2007; Lynam et al., 2007, 2010; Zorrilla et al., 2010).

Importantly, structuring a BNM can be achieved graphically, without the need for any specialist software. The structure can then be populated with knowledge elicited directly from participants in the form of probability values. This simplicity means BNMs are ideally placed for use in participatory settings; especially where each participant's knowledge of the probability of relevant causes and effects may be highly developed, but their numerical skills to formalise these as a model may be limited (Castelletti and Soncini-Sessa, 2006). Moreover, BNMs support the bi-directional computation of conditional probabilities along the causal links between parent and child variables (i.e. how will a change in the probability of states in parent variable *A* affect the probability of states in child variable *B* and vice versa) (*cf.* Ames et al., 2005; Castelletti and Soncini-Sessa, 2006; Aguilera et al., 2011). This means that a BNM can be used to infer the adjustments needed throughout a system

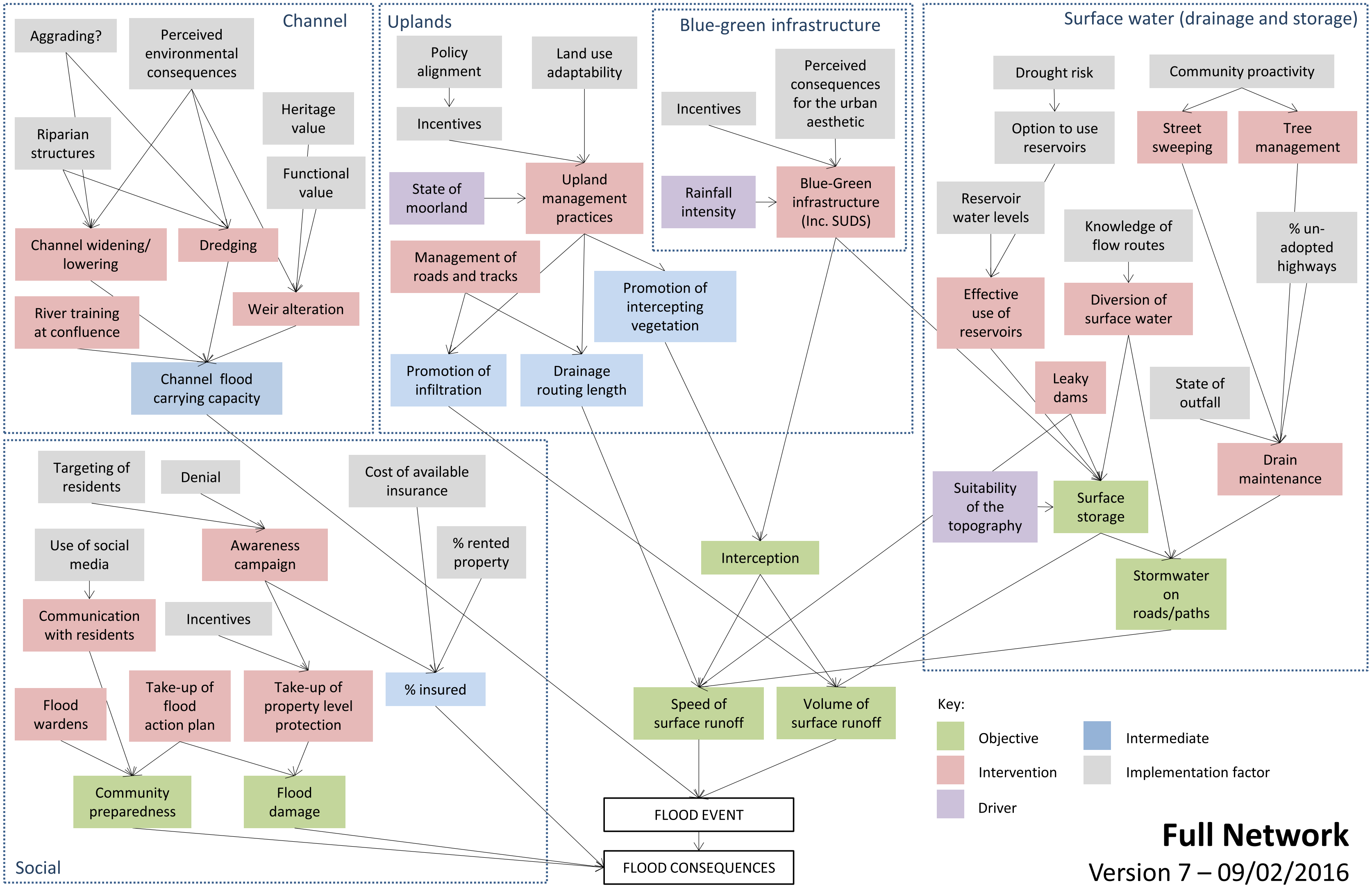

Fig. 9. The final Bayesian network model structure showing the five model sectors.

in order to maximise the probability of one or more specific objectives (i.e. a desired set of variable states) (Ames et al., 2005; Sendzimir et al., 2007). Just such a capability is an essential requirement for local FRM options identification, where the objective of the exercise is to identify which interventions, if implemented, offer the greatest probability of delivering the local flood risk objectives.

5.3. Model development and calibration

The co-development of the BNM was conducted between June 2013 and March 2014 through activities designed around a sequence of five model development workshops (Fig. 7). The recent nature of the flooding events in Hebden Bridge was beneficial to the extent that it enhanced the level of participant engagement in the workshops. However, it also introduced the probability that participants' perceptions would be biased by their specific experiences during the recent floods. To some extent this was diluted through the diversity of the participants, many of whom (e.g. local government representatives, landowners, etc.) had no first-hand experience of the flooding and were not at significant risk. Nonetheless, the inclusion of participants whose perceptions were influenced by their experience of recent events was considered appropriate, given that the purpose of the exercise was to identify local flood risk interventions options.

In workshop 1 the participants worked in small groups ($n = 5$) to parameterise the model. Working backwards from each flood risk objective, participants identified as many interventions as possible that they thought might contribute to achieving it. Participants were reminded that the intervention options could include actions to reduce the exposure and/or vulnerability of flood receptors as well as those that might disrupt flood sources and pathways. For each intervention, they then identified factors that might determine whether or not it could be implemented, factors that could control its performance if implemented, and any intermediate factors needed to explain the causality chain between the objectives, interventions, implementation, and control factors. A total of 82 variables was identified, including 18 potential interventions spanning surface water and channel management, upland catchment management, social behaviours, and the adoption of blue-green infrastructure.

In workshops 2 and 3 the participants co-developed a model structure. All of the variables from workshop 1 were transferred to coloured cards (coded according to the variable types in Table 3). In two groups, participants were asked to work backwards from the objectives; arranging and linking the variables together with edges that represented perceived cause-effect dependencies. The structures defined by the participants incorporated both definitional/synthesis and cause-consequence idioms (Neil et al., 2000). This resulted in two 'networks of causality' that documented participants' situated knowledge of intervention options that might help to achieve the flood risk objectives for Hebden Bridge, and the dependencies that could determine their success (Fig. 8). Each network was photographed. These networks were then iterated and refined in workshop 3 with the participant groups working through each variable, confirming the parent variables that could affect its state, removing erroneous relationships, and adding any additional variables where they were felt to be missing.

Between workshops 3 and 4, the University of Nottingham researchers and staff from the Environment Agency concatenated the participants' networks into a combined version (Fig. 9); removing duplicate cause-effect structures and streamlining where necessary to remove intermediate variables. The final network was organised according to the different sectors of the flood risk system represented within the variable set (e.g. channel, upland catchment, surface water (drainage and storage), social and blue-green infrastructure). Of particular importance to this process are recent arguments which assert that the use of traditional 'risk = probability x impact' structures are invalid in the case of Bayesian networks (Fenton and Neil, 2013). The participants' initial structuring of flood risk (which reflected the traditional structure) was adjusted so that it reflected a 'trigger, event, consequence, control and mitigant' structure which is advised for use in Bayesian network-based risk assessment.

All variables in the sectors were instantiated with discrete, qualitative binary states (e.g. High/Low; Desirable/Undesirable) as a pragmatic response to the constraints on model complexity imposed by Principles 2 and 3 of the participatory modelling process (Section 3). We recognise that more complex discrete variables are regularly used in BMNs to overcome the limited resolution that binary variables permit. However, established methods for modelling the large number of conditional probabilities that must be populated in the CPTs of ranked variables are best applied where participants have a moderate degree of statistical expertise (*cf.* Fenton et al., 2007: 7). Moreover, benchmarking experiments reveal that the time required to do this can extend to several days, even in a relatively small BNM (ibid: 9). Thus, the use of ranked variables was considered desirable but impractical in this project. Similarly, it could be argued that the simplification imposed by use of qualitative variables throughout prevented the inclusion of numeric formalisations (supported by dynamic discretisation (Neil et al., 2007)) that could have been more appropriate for some variables (e.g. the 'cost of available insurance' variable was assigned states 'High' or 'Low' rather than real cost values). This decision was taken in order to maximise the ease with which tacit knowledge (which is an 'essential complement to explicit knowledge' (Gertler, 2003:78)) could be reflected in the model (Gacitua et al., 2009), and to preserve its 'perceptions-driven' nature (see Principle 2, Section 3). Indeed, the construction of a perceptions-driven model was sought as a response to local FRM legislation in the UK which has increased the influence of stakeholder *perception* in FRM decision-making processes – even if it is not clear that the perception is supported by quantitative evidence (see Thaler and Priest (2014) for a recent exploration of the issues).

In workshop 4 the conditional probability values needed to populate the model variables' CPT were directly elicited, with the remaining values being extrapolated in order to enhance the efficiency and reliability of CPT population (Zagorecki and Druzdzel, 2004). The elicitation process was based upon group consensus, following the principles outlined in Renooij (2001). For all elicitation tasks, participants examined each model sector in small groups ($n = <5$) and the elicited values were an agreed representation of the group's collective view. In an effort to minimise motivational and/or cognitive bias (Skinner, 1999), the groups consisted of both

Table 4
Elicited and extrapolated conditional probability values for a child variable with three binary parents using Cain's method and Noisy-OR. Elicited values are presented in regular font. Extrapolated values are presented in bold italic font.

Parent variable state			$P(Z_H\|ABC)$ Cain	$P(Z_L\|ABC)$ Cain	$P(Z_H\|ABC)$ Noisy-OR	$P(Z_L\|ABC)$ Noisy-OR
A	B	C				
H	H	H	0.95	0.05	0.95	0.05
H	H	L	0.9	0.1	0.9	0.1
H	L	H	0.7	0.3	0.7	0.3
H	*L*	*L*	***0.663***	***0.337***	***0.599***	***0.401***
L	H	H	0.3	0.7	0.3	0.7
L	*H*	*L*	***0.284***	***0.716***	***0.257***	***0.743***
L	*L*	*H*	***0.2***	***0.8***	***0.2***	***0.8***
L	L	L	0	1	***0.18***	***0.82***

Table 5
Example output from participant testing activity.

Interventions	Objectives	Preparedness and public safety	Flood damage	Flood consequences	Flood risk
Communication with residents	Ranked expected change	1	2	3	4
	Ranked observed change	1	4	2	3
	Comments:				
	Unclear definition of flood damage compared to consequences.				
	We feel residents can have only limited impact on protecting themselves compared to public agencies.				
Awareness campaign	Ranked expected change	1	=2	=2	3
	Ranked observed change	4	2	1	3
	Comments:				
	Odd that awareness campaign doesn't change preparedness.				
	Could this be a problem with the original concept (e.g. awareness campaign vs. communication with residents)?				

expert practitioners and local stakeholders, and group membership was varied for each elicitation task. Elicitation was conducted one variable at a time, limiting focus to each individual child variable and its parents. While multiple repetitions of the elicitation process for each variable would have further enhanced the robustness of the data (enabling formal testing for bias and uncertainty), achieving this in Hebden Bridge was impractical due to the relatively short time available to complete the participatory modelling process (6 workshops) and the size of the BNM that the participants produced (comprising 59 variables).

Cain (2001) method was used to populate CPTs on the basis of a small number of values elicited from participants. By contrast, the prior probabilities contained in the CPTs of variables at the network margin (i.e. the implementation or control factor variables that determine the boundary conditions in which the flood risk system represented in the BNM operates) were fully elicited from the participants so that they reflected the perceived ‘current conditions’ in Hebden Bridge (*cf.* Smith et al., 2007). Cain's method has similarities to the popular Noisy-OR gate approach (Diez, 1993; Huang and Henrion, 1996; Onisko et al., 2001; Anand and Downs, 2008) which uses two elicited end member states (rather than one) to constrain extrapolated values. Like Noisy-OR, it ensures logical consistency in the elicited probabilities and reduces the number of probabilities that need to be elicited from stakeholders (Smith et al., 2007; Bashari et al., 2009, see also Bromley, 2005; Chen and Pollino, 2012). The following worked example exemplifies the method and its key assumptions, with the results contrasted against using Noisy-OR to populate the same CPT.

A conditional probability table for a binary child variable (Z) with three binary parent variables (A, B, C) is presented in Table 4. All variables have states High (H) and Low (L). Conditional probabilities for the eight possible parent variable state combinations are required to populate the table. Five of these have been elicited. $P(Z_H|A_HB_HC_H)$ and $P(Z_H|A_LB_LC_L)$ are end members that determine the upper and lower limit of the conditional probability values in the table. The proportional difference between $P(Z_H|A_HB_HC_H)$ and $P(Z_H|A_HB_HC_L)$ reflects the independent impact of changing the state of parent variable C from High to Low. Similarly, the proportional difference between $P(Z_H|A_HB_HC_H)$ and $P(Z_H|A_HB_LC_H)$ reflects the independent impact of changing the state of parent variable B, while the proportional difference between $P(Z_H|A_HB_HC_H)$ and $P(Z_H|A_LB_HC_H)$ reflects the independent impact of changing the state of parent variable A. These proportional differences become the extrapolation factors that are used for estimating unknown values of $P(Z_H|ABC)$.

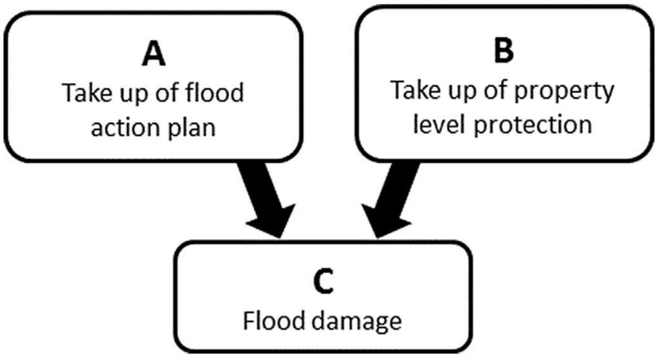

Fig. 10. A simple directed acyclic graph for structuring flood risk interventions (A, B) and their causal relationship with the flood damage objective (C).

For example, the unknown value of $P(Z_H|A_HB_LC_L)$ can be estimated by multiplying the elicited value of $P(Z_H|A_HB_LC_H)$ by an extrapolation factor (EF) that reflects the proportional change in conditional probability that is associated with changing parent variable C from High to Low (EF_C):

$$EF_C = \frac{(P(Z_H|A_HB_HC_L) - P(Z_H|A_LB_LC_L))}{(P(Z_H|A_HB_HC_H) - P(Z_H|A_LB_LC_L))} = \frac{(0.9-0)}{(0.95-0)} = 0.947 \tag{1}$$

$$\begin{aligned} P(Z_H|A_HB_LC_L) = {} & [P(Z_H|A_HB_LC_H) - P(Z_H|A_LB_LC_L)] \times EF_C \\ & + P(Z_H|A_LB_LC_L) = [(0.7-0) \times 0.947] + 0 \\ & = 0.663 \end{aligned} \tag{2}$$

In the same way, EF_C can also be used to estimate $P(Z_H|A_LB_HC_L)$:

$$\begin{aligned} P(Z_H|A_LB_HC_L) = {} & [P(Z_H|A_LB_HC_H) - P(Z_H|A_LB_LC_L)] \times EF_C \\ & + P(Z_H|A_LB_LC_L) = [(0.3-0) \times 0.947] + 0 \\ & = 0.284 \end{aligned} \tag{3}$$

An extrapolation factor can also be computed to reflect the proportional change in conditional probability that is associated with independently changing the states of parent variable B:

$$EF_B = \frac{(P(Z_H|A_HB_LC_H) - P(Z_H|A_LB_LC_L))}{(P(Z_H|A_HB_HC_H) - P(Z_H|A_LB_LC_L))} = \frac{(0.7-0)}{(0.95-0)} = 0.665 \tag{4}$$

This can, in turn, be used to estimate the remaining unknown conditional probability value:

$$\begin{aligned} P(Z_H|A_LB_LC_H) = {} & [P(Z_H|A_LB_HC_H) - P(Z_H|A_LB_LC_L)] \times EF_B \\ & + P(Z_H|A_LB_LC_L) = [(0.3-0) \times 0.665] + 0 \\ & = 0.20 \end{aligned} \tag{5}$$

Cain (2001) method has similar assumptions as Noisy-OR

Table 6
Results of using backwards propagation to test the sensitivity of each objective to different interventions. Percentages show the change observed in the desired state of each intervention.

Objective	Ranking of interventions (percentage change towards desired state)				
	1	2	3	4	5
Speed of surface runoff	Leaky dams (21.0%)	Management of roads and tracks (8.0%)	Diversion of surface water (5.5%)	Drain maintenance (4.9%)	Upland management practices (4%)
Volume of surface runoff	Management of roads and tracks (2.6%)	Upland management practices (1.4%)	Blue-green infrastructure (inc. SUDS) (1.2%)	Diversion of surface water (1.1%)	Leaky dams (0.5%)
Interception	Blue-green infrastructure (inc. SUDS) (5.8%)	Upland management practices (3.6%)			
Stormwater on roads/paths	Diversion of surface water (19.0%)	Drain maintenance (17.1%)	Tree management (2.9%)	Street sweeping (1.9%)	Leaky dams (1.1%)
Surface storage	Diversion of surface water (9.8%)	Leaky dams (4.3%)	Blue-green infrastructure (inc. SUDS) (3.3%)	Effectiveness of using the reservoirs (2.5%)	
Preparedness and public safety	Take-up of flood action plan (14.9%)	Communication with residents (10.0%)	Flood wardens (6.8%)		
Flood damage	Take-up of property level protection (30.8%)	Take-up of flood action plan (25.7%)	Awareness campaign (10.8%)		
Flood consequences	Take-up of property level protection (15.7%)	Take-up of flood action plan (13.3%)	Awareness campaign (7.3%)	Communication with residents (0.4%)	Flood wardens (0.3%)
Flood likelihood	Channel widening/lowering (2.6%)	River training at confluence (2.5%)	Weir alteration (1.9%)	Dredging (1.3%)	Management of roads and tracks (0.2%)
Flood risk	Take-up of property level protection (9.4%)	Take-up of flood action plan (7.9%)	Awareness campaign (4.4%)	Channel widening/lowering (1.3%)	River training at confluence (1.3%)

(Onisko et al., 2001; Fenton et al., 2007): monotonicity and conditional independence of parent variables, although the parameterisation is slightly different. In this study, the assumption of monotonicity is supported by the fact that all of the elicited conditional probabilities conformed to this structure. The assumption of conditional independence is more problematic as in reality, complex, joint dependencies between parent variables are likely. However, factoring in such dependence requires more sophisticated extrapolation methods that can model the form(s) of the joint dependencies and their influence on the conditional probabilities of the child variable states. Necessarily, some information about the form of the joint dependencies is required and in the context of participatory modelling, this would need to be directly elicited from participants. In many cases, it is unlikely that these forms will be known with sufficient specificity to inform such methods. Indeed, in Hebden Bridge the acceptance of implied independence between parent variables was a pragmatic solution to the participants' limited ability to express and formalise these joint dependencies.

Before using the model to explore flood risk intervention options in Hebden Bridge the participants completed a model calibration activity in workshop 5 (effectively a version of Edwards (1998) ‘antecedent conditions check’). The aim of this activity was to check that the behaviour of the final model conformed to the expectations of the participants; enabling erroneous model behaviours to be traced and, where necessary, rectified by adjusting the state values of the variables implicated. Each intervention represented in the BNM was ranked according to its expected impact on each of the objectives and the rankings were tabulated by the participants. The states of each intervention were then set to have maximum probability of achieving a positive change in the objectives and the rank of the observed impact on each objective was added to the tabulation. Where discrepancies in the rankings occurred, participants were asked to comment on the reasons for them, and suggest any adjustments that the BNM required. An example for two of the interventions in the social model component is provided in Table 5. Between workshops 5 and 6, University of Nottingham researchers adjusted the variable state values where large discrepancies in the rankings were observed.

6. Using the model to support intervention options identification (Stage 3)

The reasoning capability of the BNM was used to infer the relative contribution of each intervention in delivering each FRM objective via a one-way sensitivity analysis (Coupe et al., 2000). Assuming a simple case of a binary child variable C with two binary parents A and B (all with states High and Low), the marginal probability of $\mathrm{C_H}$ can be computed according to the law of total probability:

$$\begin{aligned}\mathrm{P}(\mathrm{C}_H) = \ & \mathrm{P}(\mathrm{C}_H|\mathrm{A}_H\cap\mathrm{B}_H) + \mathrm{P}(\mathrm{C}_H|\mathrm{A}_L\cap\mathrm{B}_H) + \mathrm{P}(\mathrm{C}|\mathrm{A}_H\cap\mathrm{B}_L) \\ & + \mathrm{P}(\mathrm{C}|\mathrm{A}_L\cap\mathrm{B}_L)\end{aligned} \tag{6}$$

The conditional probability of C, given A and B can be also be computed from the joint, conditional probability distribution for the two objectives (A and B):

$$\mathrm{P}(\mathrm{C}_H|\mathrm{A}_H\cap\mathrm{B}_H) = \frac{\mathrm{P}(\mathrm{A}_H\cap\mathrm{B}_H\cap\mathrm{C}_H)}{\mathrm{P}(\mathrm{A}_H|\mathrm{B}_H) \times \mathrm{P}(\mathrm{B}_H)} \tag{7}$$

Using Bayes law, it is then possible to compute the conditional probability of A given C:

$$\mathrm{P}(\mathrm{A}_H|\mathrm{C}_H) = \frac{\mathrm{P}(\mathrm{A}_H\cap\mathrm{C}_H)}{\mathrm{P}(\mathrm{C}_H)} \tag{8}$$

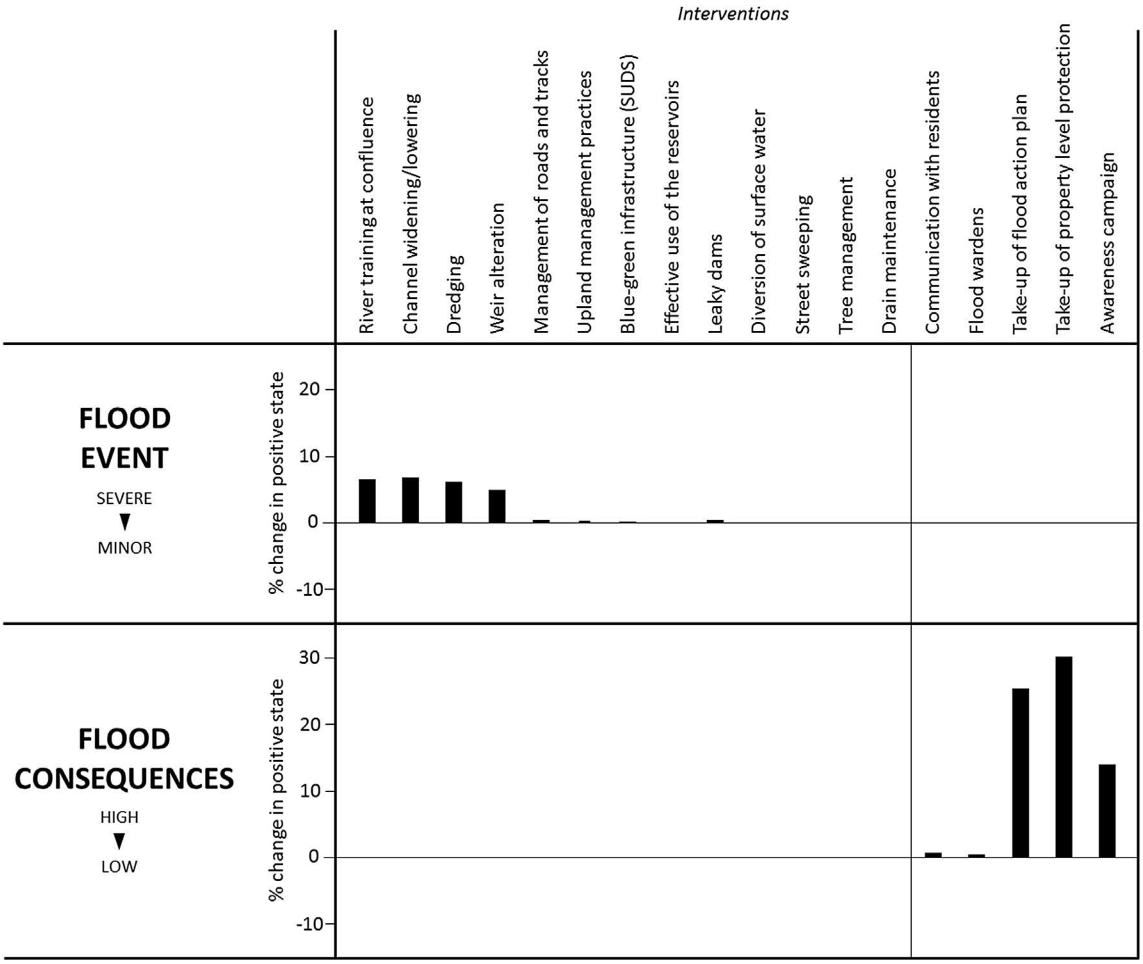

Fig. 11. Sensitivity of interventions for the minimisation of flood event and consequence variables.

Similarly, it is possible to compute the conditional probability of B given C:

$$P(B_H|C_H) = \frac{P(B_H \cap C_H)}{P(C_H)} \tag{9}$$

Eqs. (8) and (9) can be used to assess the sensitivity of variables in a Bayesian network by back-propagating the effect of changing the states of a child variable on its parents. Take, for example, Fig. 10 which shows a fragment of the Hebden Bridge BNM. The objective ‘Flood damage’ (C) is conditionally dependent on two interventions – ‘Take up of flood action plan’ (A) and ‘Take up of property level protection’ (B) (Fig. 10).

The sensitivity of intervention A (A_{sen}) to the objective C can be assessed by quantifying the effect that change to the states of C has on the states of A:

$$A_{sen} = P(A_H|C_H) - P(A_H|C_L) \tag{10}$$

Similarly, the sensitivity of intervention B (B_{sen}) to the objective C can be assessed by quantifying the effect that change to the states of C has on the states of B.

Using this approach, the strength of dependency between each intervention-objective couplet was assessed in turn by comparing the relative magnitude of their respective sensitivities. For each objective, the five interventions with the strongest dependence are presented in Table 6, together with their respective sensitivity values. It can be seen, for example, that reducing the storm water on roads and paths is highly dependent on the effectiveness of drain maintenance and the diversion of surface water. Similarly, it can be seen that the sensitivity of interventions to certain objectives (e.g. volume of surface runoff) is consistently low; indicating that the participants have low confidence that the objective can be achieved through the interventions that they have identified in the network. It should be noted that this approach assesses sensitivity of the simplified marginal probability (as defined in Eq. (7)) associated with each individual variable's states. It may be useful to extend this to include an assessment of the joint probabilities of variable states so that the priority combinations of interventions could be explored.

From the perspective of options identification, the relative magnitude of the sensitivity of each intervention to flood severity or consequence is of primary interest as this reveals the relative importance of each intervention in reducing the overall flood risk. The results for Hebden Bridge are presented in Fig. 11. Two features are particularly apparent. Firstly, the participants had the greatest confidence that interventions focussed on the modification of the river channel would have the greatest impact on reducing the severity of flooding, although there was limited confidence in the impact of more effective land and infrastructure management. Similarly, the participants had the greatest confidence in the beneficial role of awareness campaigns, effective planning and property level protection for reducing flood consequence. Secondly, the comparatively lower sensitivity of interventions concerned with reducing the severity of a flood event, versus those concerned

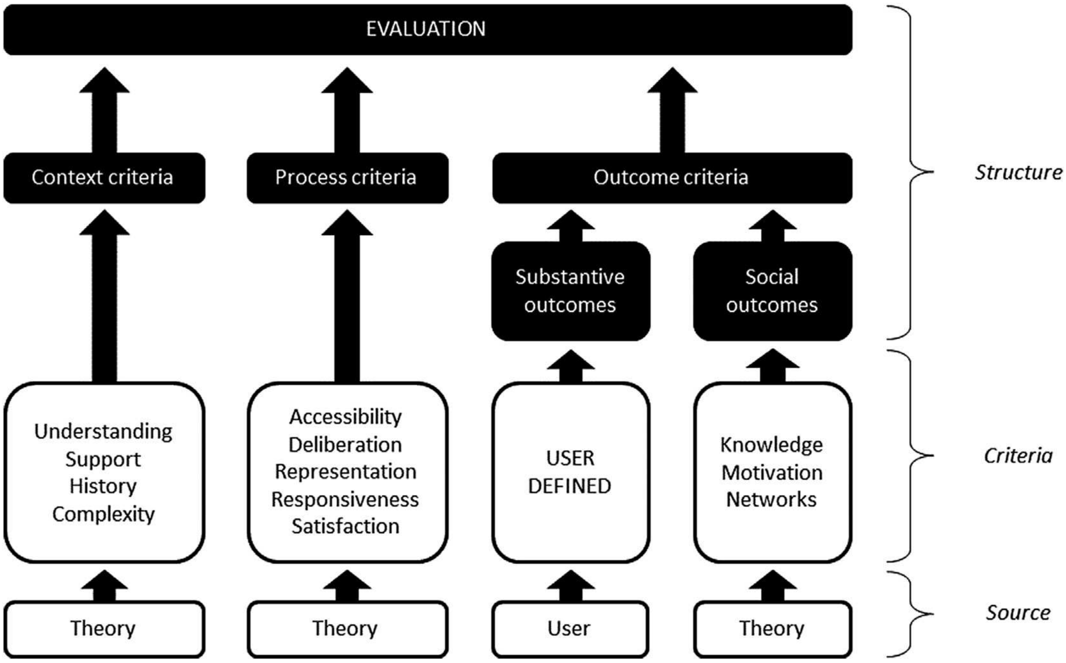

Fig. 12. The framework used to evaluate the participatory modelling process in Hebden Bridge showing the sources of evidence from which criteria were developed.

with reducing flood consequence, highlights the overriding confidence afforded to interventions aimed at enhancing flood resilience in Hebden Bridge. Indeed, this highlights the importance of including interventions aimed at reducing flood vulnerability in future options appraisal processes for the town, alongside those aimed at reducing flood probability, and the support that local stakeholders are likely to have for this.

7. Evaluation

The evaluation framework used to assess the participatory modelling process was derived by conflating the frameworks of Beierle (1999), Rowe and Frewer (2000), and Webler and Tuler (2002) so that the benefits and drawbacks of i) the process itself and; ii) its outcomes were assessed (Fig. 12).

7.1. Process evaluation

Normative and instrumental benefits (see Section 2) of the participatory modelling process were evaluated against ‘Process Criteria’ (Fig. 12) which assess the process itself and the extent to which the organisation, activities and tools used were able to support the active participation of all participants in the model's co-development and testing (*cf.* Fiorino, 1990; Beierle and Konisky, 2000; Halvorsen, 2001; Butterfoss, 2006). They are synthesised from >30 published evaluations of participatory modelling processes conducted across a diverse range of disciplines and are listed and described in Table 7, along with the literature from which they are synthesised.

Criteria 1 and 2 relate to the accessibility of the process: the ability to involve a wide range of stakeholders in model development and calibration, through simple graphical interfaces and low complexity methods (Webler et al., 2001; Prell et al., 2007; Ramsey, 2009). Where responses focussed on the accessibility of the activities, resources and language used (Criterion 1), most respondents found that they easily grasped the fundamental concepts, and that this basic level of understanding was sufficient to benefit from participating. Generally, participants found that effective communication outside of the workshops supported accessibility. It was noted that additional resources (e.g. a user manual) would be required to support use of the model outside of the process.

Criterion 3 relates to the extent to which the process is deemed to be deliberative, measured by the quality of communication within the participatory group, the degree to which consensus is sought, and the fairness of discussions (Beierle and Konisky, 2000). Several respondents valued the opportunity to hear one another's views, and noted that the discussions held during model co-production were one of the most useful process outcomes. While the group were uncertain on whether consensus was achieved, most responses suggested a move towards consensus, and a softening of extreme views.

Criteria 4 and 5 relate to whether the participant group and the resultant outcomes were representative of the community. Responses relating to the representativeness of the group (Criterion 4) suggest that the group was biased in favour of community stewardship, and lacked a desired balance between ‘specialist’ stakeholders and ‘lay’ residents. However, the participants that were involved with the process felt that they were able to engage in open discussion, in an environment where experts and non-experts worked alongside one another as equals (Criterion 5).

Criteria 6 and 7 relate to the responsiveness of the process: whether the approach and the tools used to support it were flexible to the needs of the participants, and the individual local context (Prell et al., 2007; Voinov and Gaddis, 2008). Participants commented on the ability of Bayesian networks to capture system complexities, conflicting opinions and management options; although it was contested as to whether these were specific to the Hebden Bridge area. They praised the holistic nature of the model for capturing the interconnectedness of the flooding issue, but believed that as the scope of the model widened, the solutions it proposed became less specific.

Much of the difficulty in designing participatory processes stems from the way in which different participant groups define the process as ‘effective’ (Fig. 13). For example, the views of residents (a

Table 7
Criteria and findings from the participatory process evaluation.

Criterion	References	Key findings
Accessibility		
1. Participatory activities, resources and language were designed such that all participants could fully engage, regardless of skills and experience 2. Clear and frequent communication kept the modelling process transparent	Godschalk and Stiftel (1981); Young et al., 1993; Rowe and Frewer (2000); Abelson et al. (2003); Hare et al., 2003; Prell et al., 2007; Ramsey (2009)	- Fundamental concepts understood - Requires expert facilitation - Method and model accessible to non-experts - Stakeholder communications between workshops were effective
Deliberation		
3. Participatory activities fostered knowledge exchange, debate and consensus building	Susskind and Cruickshank (1987); Kemmis (1990); Dryzek (1997); Smith and Wales (1999, 2000); Beierle and Konisky (2000); Halvorsen (2001); Abelson et al. (2003); Hartig et al. (2010).	- Useful to hear each other's' views - Model building generated discussion - Group started to build consensus
Representation		
4. The participants are representative of the affected community and the full range of views 5. All participants were given opportunity to make a substantive contribution	Crosby (1995); Phillips (1995); Webler (1995); Hartig et al. (1998); Beierle (1999); Smith and Wales (1999, 2000); Halvorsen (2001); Abelson et al. (2003); Butterfoss (2006).	- Group was not totally representative of community - Although residents were recruited, most participants were representatives of organisations - Discussions were open - Process gave participants an equal standing
Responsiveness		
6. Participatory tools were chosen according to local objectives, resources and available data 7. The participatory process was flexible to change, with the agenda and activities shaped by the needs and goals of the participants	Fiorino (1990); Webler (1995); Beierle and Konisky (2000); Prell et al. (2007); Voinov and Gaddis (2008); Ramsey (2009); Voinov and Bousquet (2010).	- Model generally based on opinions of those participating - Process identified key variables - Possible to see own input in the model - Model allowed testing of scenarios
Satisfaction		
8. Participatory processes were facilitated in a professional and effective manner 9. The participants knew what was expected of them and what they could expect to gain from participating 10. The process had clear purpose, objectives and direction	Rogers et al. (1993); Hartig et al. (1994); Butterfoss et al. (1996); Beierle (1999); Chess and Purcell (1999); Kenney et al. (2000); Halvorsen (2001); Butterfoss (2006)	- Tasks were well-structured - Thinking time was provided between workshops - Process required a large (but not unreasonable) time commitment - The process became clearer the more sessions one attended - A useful addition early in the flood risk management process - The process became clearer the more sessions one

particular group which active participation seeks to involve in the modelling process) are not always aligned with those of other groups. Specifically, residents rarely referred to knowledge exchange and deliberation (Criteria 3 and 5), implying either that these activities were not highly valued, or that the process could have delivered these better by being more accessible to non-experts. In contrast, local government and regulator mentions for both of these criteria (in addition to Criteria 7) were high, suggesting that they value these activities as central to an effective participatory process, but have overestimated the accessibility of this particular case, possibly as a result of their broader experience and expertise. Finally, Fig. 13 illustrates the importance ascribed to having a modelling group which is representative of the local community (Criterion 4). Individual comments from interviews suggest that most respondents felt the group could have been more representative.

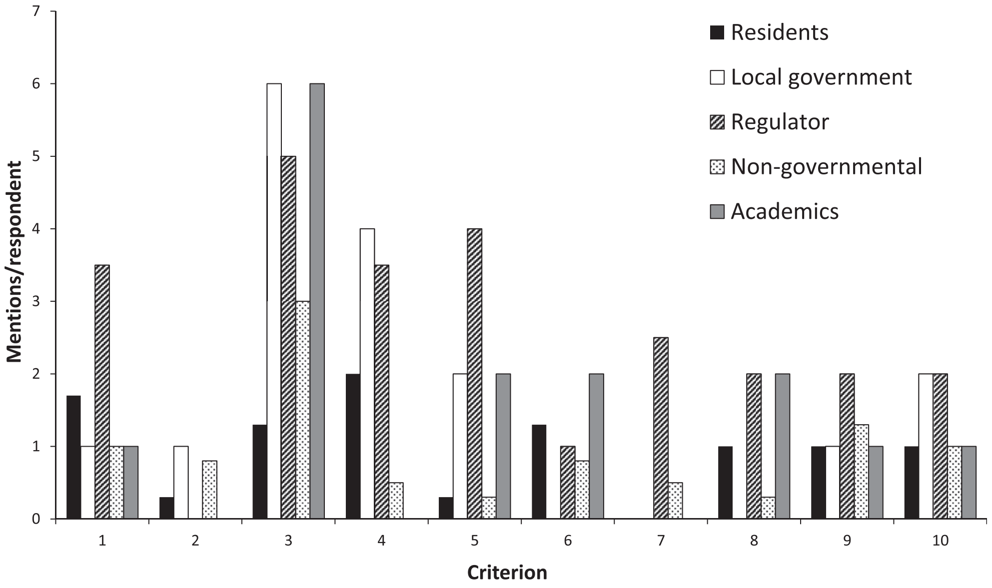

Fig. 13. Criteria mentions per participant group during process evaluation (ordered by criterion).

Table 8
Criteria and findings from the substantive outcomes evaluation.

Criterion	Mentions by organisation		Key findings
	EA	CMBC	
Model is accessible and available to those outside of the participatory group	13	1	• Model should be made available as an educational tool • Software is generally easy to use, but would require supporting documentation
Flooding is seen as a complex issue with multiple solutions	9	6	• Process raised awareness of the complex nature of flooding • People are general better informed about flood risks • Process identified options that could be explored further
Residents gain an understanding of how to reduce their own flood risk	2	5	• Model showed various actions an individuals could take • Process encouraged generation of ideas for small-scale solutions
Community priorities were highlighted	4	1	• Results from the process could be useful for agenda setting • Useful when strategic thinking is the main objective
General public has realistic expectations of agencies	9	5	• Difficult to measure whether expectations have changed
Residents understand they have a personal responsibility	1	5	• Process demonstrated a need to share responsibilities • Surprise at level of community enthusiasm and unity
Flooding is maintained as a priority in the community	3	3	• Interest in flooding remains several years after event
Participation is increased or maintained	14	11	• Process took participation to a higher level • Feedback from the process was positive • Impact on participation small compared to a flooding event
Individual action (change in behaviour) was promoted and taken up	4	3	• Change in behaviour attributed to a gaining of knowledge • Slight increase in adoption of property level protection
Community action (change in behaviour) was promoted and taken up	3	4	• Existing groups are now open to new ideas, as a result of what they have learnt • People now look at the multiple benefits of their actions (including reducing flood risk)

7.2. *Substantive outcomes evaluation*

Substantive outcome criteria assess the outcomes of the participatory process against those with the primary responsibility for implementing its results, with particular emphasis on the ability of the process to deliver evidence. In Hebden Bridge, substantive outcome criteria assess the extent to which the participatory model facilitated the identification of new intervention options that could feed into a subsequent appraisal process (i.e. substantive benefits). These were developed from iterative, *in vivo* coding (Given, 2008) of transcripts of semi-structured interviews ($n = 4$) with staff at the Environment Agency (EA) and Calderdale Metropolitan Borough Council (CMBC), the principal flood risk management decision-makers for Hebden Bridge. These criteria, along with key findings, are presented in Table 8.

Representatives from the EA identified three main benefits. The first was the accessibility and availability of the model as an educational tool, and its potential for use by those not involved with its generation. The second concerned the improvement in each participant's understanding of the complexities of flooding and an appreciation of the need for multiple and innovative interventions. The third considered the identification of community priorities for the management of flooding. On several occasions, respondents suggested that results from the participatory modelling process could be used to inform and guide other flood risk management activities that do not have such an active level of participation.

Representatives from CMBC focussed on flood resilience in the community. Responses centred on residents gaining an understanding of actions they can take to personally contribute towards a reduction in flood risk; building the capacity to take those actions; and fostering a sense of personal responsibility to do so.

7.3. *Social outcomes evaluation*

The extent to which the participatory modelling process facilitated new knowledge and understanding of local flood risk processes and interventions amongst the participants engaged in its co-development (i.e. delivered instrumental benefits through its agency as a facilitator of beneficial social change and enhanced community resilience (e.g. Cutter et al., 2008)) was assessed using ‘Social Outcome Criteria’. These were derived from >15 studies exploring the relationship between social capacity and community resilience (Kuhlicke et al., 2011), and structured using Buchecker's three components of social capacity (knowledge, motivation and networking (Buchecker et al., 2013)). These criteria, along with key findings, are presented in Table 9 and Fig. 14.

Criteria 1–3 relate to knowledge capacity: the efficient use and sharing of knowledge within a community that empowers individuals to work effectively in teams, establishes information channels, increases risk perception, and enhances a sense of personal control (Beretta, 2005; Höppner et al., 2010, 2012). Responses highlighted the value participants placed on sharing local knowledge, and using that knowledge to build better models (Criterion 1). These discussions encouraged participants to think about multiple risks, the interconnectivity of system elements, and novel solutions that could help to reduce flood risk (Criterion 2). Further, it

Table 9
Criteria and findings from the social outcomes evaluation.

Criterion	References	Key findings
Knowledge capacity		
1. Participants shared in the coproduction of knowledge on local flood risks (including hazard, exposure and vulnerability) 2. Participants discussed their perceptions of risk, and explored a range of interventions that could mitigate them 3. Participants know who to go to for support within and outside of the community, and feel better prepared for another flood event	Folke et al. (2005); Howgate and Kenyon (2009); Nobert et al. (2010); Höppner et al. (2012); Buchecker et al. (2013)	• Stakeholders learnt from each other • Awareness raised of importance of local knowledge • Potential for generating novel and innovative solutions • Model allowed exploration of different interventions • Useful opportunity to talk with experts • Useful to meet and get to know other stakeholders
Motivation capacity		
4. Participants feel motivated to take ownership and responsibility for taking a proactive role in the reduction of local flood risk 5. Participants identified a range of appropriate interventions that could be implemented by either individuals and/or the community	DeLong and Fehey (2000); Uphoff (2000); O'Neill (2004); Deeming (2008); Buchecker et al. (2013)	• Empowers local people to get more involved • Flood resilience came through as a strong theme • Model looked beyond the usual interventions • Developed understanding that there was no single solution
Network capacity		
6. Relationships were developed between participants from both within and outside of the local flood risk community 7. Trust was developed between participants from both within and outside of the local flood risk community	Putnam (1993, 2000); Pelling (1998, 2003); Ardichvili et al. (2003); Folke et al. (2003); Chazdon and Lott (2010); Buchecker et al. (2013)	• Stakeholder relationships were improved • Useful way of getting stakeholders to work together • All participants were seen and treated as equals • Discussions were open and people were willing to listen

facilitated stakeholder networking, promoted positive engagement between practitioners and residents, and helped improve understanding of different stakeholders' roles (Criterion 3).

Criteria 4 and 5 relate to motivation capacity: the existence of established norms that promote trust, where active involvement in knowledge-exchange activities and support of community initiatives are seen as moral obligations (Hayes and Walsham, 2001; Ardichvili et al., 2003). Participants valued the opportunity that participation afforded them to get more involved in decision-making, share responsibilities, and take the lead on flood resilience issues (Criterion 4). The process further demystified the notion that there was one single solution to flooding in Hebden Bridge, that any solution would require a combination of appropriate interventions, many implemented by the community themselves (Criterion 5).

Criteria 6 and 7 relate to network capacity: the building of mutually beneficial social relationships between individuals and groups, both within and outside of the community, that foster feelings of social connectedness, support, resilience, and adaptability (Putnam, 1993, 2000; Folke et al., 2003, 2005). Participants saw the process as a useful means of getting individuals and organisations to meet, work together, and discuss their views and roles (Criterion 6). The building of trust (Criterion 7) was mainly discussed with reference to equality and openness between participants, allowing them to engage with new ideas.

The ways in which different groups value the social outcomes of participatory processes further reinforce the different ways participants are framing participation in flood risk management (Fig. 14). Both local government and non-governmental organisations felt that participation developed relationships both within and outside of the flood risk community (Criterion 6). As responsibilities are increasingly devolved to local levels, relationships between local organisations will become ever more important for effective FRM. In contrast, responses from the EA centred on identifying and exploring different flood risk interventions (Criteria 2 and 5), especially where members of the community can take a more active role in their implementation (Criterion 4); indicative of a need to move beyond traditional engineering solutions. Finally, the similarities in responses related to community intervention (Criteria 4 and 5) could suggest a shift towards (or a response to) the sharing of responsibilities.

8. Lessons for local flood risk management

While the importance of participation in environmental management is supported by legislative enthusiasm, it has largely remained limited to consultation in flood risk decision-making. Practitioners are understandably cautious about initiating more comprehensive participation. Advice and practical guidance on how to make flood risk modelling more participatory is sparse, and studies have shown that ineffective participation can damage relationships and trust. Yet, as the responsibilities and costs of managing flood risk are increasingly devolved to local levels and shared amongst a growing number of stakeholders (Thaler and Priest, 2014), participatory models offer a mechanism for involving a breadth of stakeholders in decision-making. Crucially, they provide a means by which tacit and situated knowledge can be captured represented and used – an outcome that is increasingly seen as critical to mitigating flood consequences through the identification of social and behavioural solutions as well as

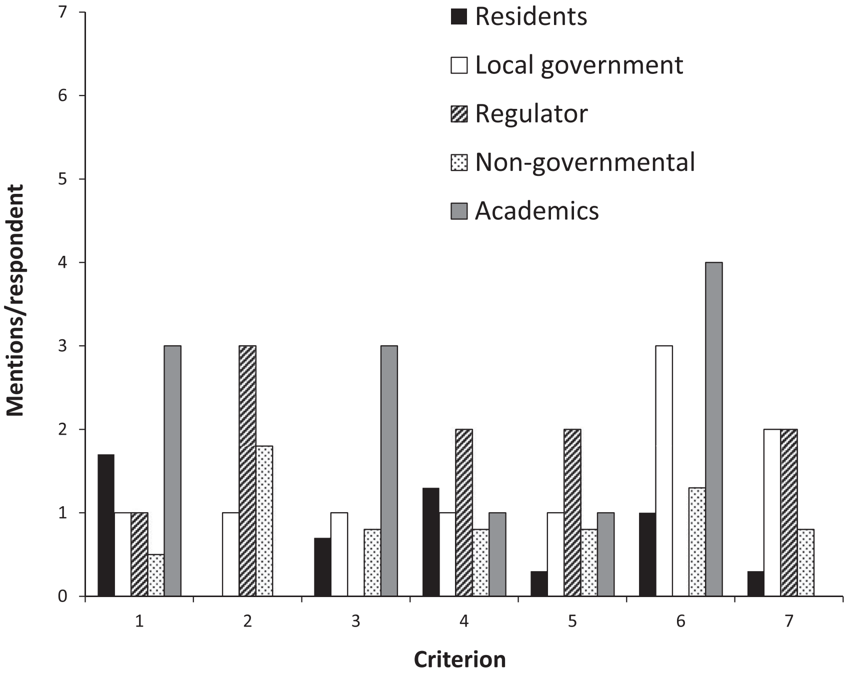

Fig. 14. Criteria mentions per participant group during social outcomes evaluation (ordered by criterion).

engineered ones.

The study presented here challenges some of the common critiques of participation and participatory modelling. It contests the assertion that participation fosters a post-political condition with no space for conflict and disagreement (Tsouvalis and Waterton, 2012). The process evaluation revealed that knowledge exchange and debate were fostered, and that the participatory model development acted as a focus for consensus-building. Similarly, the notion that flood risk is understood by non-experts as a series of unchallengeable 'facts' is demonstrably not the case in Hebden Bridge. Here, the participatory modelling processes provided an opportunity for the 'open public framing' (Wynne, 2007) of flood risk problems which is complementary to, yet discrete from the numerical models designed to quantify and reduce flood probability. Indeed, the substantive evaluation (Table 8) highlights how the approach is viewed as complementary to more established FRM activities and how the case study represents a valuable blueprint for other flood risk management activities. It also highlights the practitioners' recognition that small-scale interventions, enacted by individuals and/or the community have to potential to be extremely important interventions in local FRM contexts.

From a methodological perspective, the study reveals the efficacy of BNMs as tools for helping to assess the broadest range of potential options (many of which will be community-driven social solutions that are difficult to integrate into traditional numerical models) in a participatory options identification process. It also highlights its value as a means of exploring which of these might merit further exploration. We assert that the strengths of the BNM method extend beyond the numerical outputs that are produced. They include the relative ease with which both explicit and tacit knowledge about flood risk cause and effect can be structured and formalised by stakeholders and the ability to reveal misconceptions and gaps in this causal knowledge alongside insights into stakeholder perceptions of flood risk and solutions for addressing it. Both are of value to flood risk practitioners.

The study also highlights several important challenges. Working with a diversity of stakeholder participants inevitably involves a diversity of opinion and individual bias that may be impacted by the recentness with which flooding has been experienced. Methods need to account for the fact that the participants with the loudest voices do not necessarily possess the greatest knowledge. The evaluation we present highlights the extent to which a flooding event can act as an agent for mobilising the community (*cf.* Lane et al., 2011), but it does not reveal the optimum time to organise a participatory FRM process. The study also highlights that, where participants have limited technical and/or numerical capacity, very high levels of conceptual and numerical simplification must be applied to the representation of the local flood risk system if the participatory model is to be accessible and meaningful to the participants that develop it. In this case, simplification included the limitation of variables to qualitative binary states – reducing the resolution of the model and limiting the extent to which it could be informed by data. Despite this, the technique achieved its goal of informing a shortlist of intervention options for Hebden Bridge that warranted further appraisal which incorporated both social and behavioural as well physical and engineered interventions (Fig. 11).

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