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A Systems Approach to Flood Vulnerability

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ABSTRACT

Flood vulnerability is an internationally important problem with no easy solution. In this paper it is argued that vulnerability is an emergent output of interacting human and engineering components, and that to make further progress on usefully deploying the concept, a systems approach is needed. The existing state of the art in Flood Vulnerability Indices is blended with a constraints-based systems engineering approach called an Abstraction Hierarchy. Four existing towns were modelled using this approach, and the impact of a 1-200 year flood was assessed, by focusing on the key interactions within the model. As the flood waters progressively removed physical objects in the system, higher level processes and functions became systematically degraded. Via this process, the modelled towns were revealed to be low on exposure, high on susceptibility, but low on resilience. This is one of eight vulnerability types possible. Different flood risk solutions can be associated with different vulnerability types. Comparing these outputs to real life policy and practice reveals some interesting areas of mismatch.

Keywords: flood vulnerability, exposure, susceptibility, resilience, flood management

INTRODUCTION

A nation's critical infrastructure needs to be able to withstand disturbances as they happen, then bounce back afterwards. Most nations have the equivalent of a National Risk Register (e.g. Cabinet Office, 2013). In the UK it presents a range of civil emergencies with a greater than 1 in 20 chance of occurring in the next five years, and with the potential to yield impacts ranging from social disruption and economic harm through to widespread illness and fatalities. Flooding is a prime example (p. 10). The ability of daily life to continue in the face of disturbances like this does not depend on a single engineering solution; rather on the ability of organisations, infrastructure and individuals to anticipate the changing shape of risk before failures and harm occur, then to respond in effective ways when it does. This paper puts the latest research on flood vulnerability in touch with a novel systems method, enabling this wider view to be captured explicitly. Several real towns were modelled and subject to a simulated 1 in 200 year flood event. The method shows how critical functions and processes at higher levels of system abstraction are progressively degraded as individual 'physical objects', at low levels of abstraction, are flooded. In addition, metrics are extracted from the model to enable each town to be characterised in terms of its vulnerability, and positioned in a universal 'vulnerability space'. Solutions for improving resilience vary depending on what region of the space is occupied, and the method can be deployed to determine this for any town in any region of the world. First, the concept of vulnerability is defined, the role of systems thinking explained, and the specific method to be employed (and extended) presented.

Defining Vulnerability

The concept of vulnerability is often used within natural hazard, disaster and environmental change research. Many authors have discussed and attempted to define this concept (e.g. Adger, 2006; Lewis, 1999; Van der Veen and Logtmeijer, 2005). The IPCC definition (McCarthy, 2001) states that vulnerability is: the degree to which a system is susceptible to, and unable to cope with, adverse climate change effects. A comprehensive discussion on vulnerability can be found in Balica et al.

(2009) and Balica and Wright (2010), and its importance is difficult to overstate: according to some authors 'vulnerability is the root cause of disasters' (Lewis, 1999). This paper focuses on the issue of vulnerability to the natural hazard of flooding, and within this context a functional definition of vulnerability is required.

There have been numerous attempts to define flood vulnerability (e.g. Kazmeirczak and Cavan, 2011; Giupponi et al., 2013; Li et al., 2013; Balica et al., 2013). Common to them all is the division of vulnerability into certain component parts. There is some consensus about what these parts should be, with vulnerability incorporating concepts of susceptibility, exposure and resilience. Exposure can be considered the tangible and intangible goods and services, possessing value of some kind, which may be subject to flooding. Susceptibility is the extent to which such elements are exposed, which in turn influences the chance of being harmed at times of hazardous floods (Balica et al., 2009). Resilience relates to adaptive capacity and so-called 'bounce back' (Adger, 2006). Balica et al., (2009, 2013) define flood vulnerability as:

"the extent to which a system is susceptible to floods due to exposure, a perturbation, in conjunction with its ability (or inability) to cope, recover, or basically adapt" (Balica et al, 2009, p. 2572).

According to this definition, vulnerability can be imagined as a three dimensional space with exposure, susceptibility and resilience forming the main axes (Figure 1). A town (or any other system under analysis) will fall into a particular region of the three dimensional space depending on the components which define the type of flood vulnerability. For example, a region may have high exposure combined with a population at risk (i.e. a city such as Rotterdam in the Netherlands or Ho Chi Minh City, Vietnam), leading to high susceptibility. A geographical area that has high exposure but is predominantly uninhabited, such as agricultural land prone to flooding (e.g. areas along the Mekong river used for rice production during the wet season), could be said to have low susceptibility and high resilience. The key issue is that the interventions required are likely to differ across vulnerability types. Using the three dimensional vulnerability space, vulnerability 'solutions' can be scrutinized for their match to vulnerability 'type'. For example, high resilience in a population can be encouraged through flood proofing of structures and businesses, education, and robust flood warnings. Exposure can be reduced using hard engineering interventions such as flood defences or reservoir storage in the upper catchment. Susceptibility can be addressed via planning restrictions and other means that reduce the chance of damage and destruction due to flooding. The possible engineering solutions are, to some extent, plentiful. This reflects the typical focus of flood risk management. The conceptual challenge is to define what type of vulnerability a location possesses, and to respond with optimum (not necessarily engineering), solutions.

Figure 1 – The three dimensions of vulnerability intersect to create a coordinate space, or cube, into which specific sites would fall

Traditional and Parametric Approaches to Modelling Flood Vulnerability

Floods are primarily the result of extreme weather events. The magnitude of extreme events has an inverse relationship with the frequency of their occurrence, so floods with high magnitude tend to occur less frequently than more moderate events. The relationship between the frequency of occurrence and its magnitude is traditionally established by performing a frequency analysis of historical hydrological data using different probability distributions. Once the frequency, magnitude, and shape of the hydrograph are established, computer models which discretise the topographical river and land form are used to estimate flood depth, flood elevation and velocity (Hartano et al., 2011). The results from a computer model can then be used for loss estimation due to a particular design flood event. Loss estimation, however, does not cover the full remit of vulnerability. As a result, vulnerability estimation using more traditional approaches is difficult and open to interpretation (Balica et al, 2013).

To overcome these challenges a more recent innovation has been the development of parametric approaches that attempt to quantify flood vulnerability. An example of this is the Flood Vulnerability Index (FVI) method as developed by Balica et al. (2009). This is an indicator-based methodology that aims to identify hotspots related to flood events in data rich and/or data scarce areas around the world. The main concept consists of determining the spatial scale of the analysis (e.g. river basin through to urban area), then assessing the place on a battery of individual indicators in order to arrive at four high level characteristics (social, economic, environmental and physical). From this, actions to diminish focal spots of flood vulnerability can be identified and action plans to deal with floods and flooding put in place (for a full account see Balica et al., 2009). Methods such as these have an important role to play, and while they attempt to capture the softer and more difficult to define aspects of vulnerability, they still rely on an ostensibly deterministic logic. In other words, the focal spots of flood vulnerability are decomposed into elements that are counted or otherwise analysed separately. The FVI approach is taxonomic – which has many practical advantages – but in complex sociotechnical systems like the catchments and settlements that form the subject of flood risk analyses, there are opportunities to go further.

Systems Approach

There is an argument to say that vulnerability arises from the interaction of human and engineering components within a system, be it an entire catchment or an individual town. In effect, what we are measuring with traditional and parametric approaches to flood vulnerability are the collective effects of these interactions. Vulnerability, then, is an emergent property: a phenomenon wherein “complex, interesting high-level function is produced as a result of combining simple low-level mechanisms in simple ways” (Chalmers, 1990, p.2). Emergence presents a problem for the modelling of flood vulnerability because “as systems become more complex […], self-organisation appears at more than one level […]. Such systems have multiple, hierarchical levels of self-organisation, and calculation of system level emergent properties from the component level rapidly becomes intractable" (Halley and Winkler, 2008, p. 12). In other words, the output being sought (i.e. a measure of 'vulnerability') is not easy to achieve based on an understanding of components of the system in isolation.

An alternative approach is to create a functional structure of the system in question and the possibilities and constraints within it which shape behaviour (Naikar, 2013). The analogy often given is the 'ant on a beach' (Simon, 1981). Looked at in isolation, the trajectory of the ant looks un-patterned and random. Only when the environment (and the physical constraints) are overlaid does the trajectory make sense. This is the essence of the constraints-based approach being deployed in this paper. There is, however, a broader interpretation of constraints in that they are not merely physical constraints restricting movement through a landscape, but behavioural constraints influenced by a myriad of features, ranging from rules and procedures through to social and cultural norms. Systems thinking enables the full diversity of these constraint types to be included in the model of the system in question, whether it Is an individual town or an entire catchment. It also confers a number of other, more specific, advantages. Most notable for present purposes is that the model is 'event independent'. It "provides a basis for reasoning about any situation, including those that are novel and unanticipated" (Naikar, 2013, p. 23), such as major flood events.

METHODOLOGY

Study Design

The concept of vulnerability will be explored by applying a systems-based method to four towns. The purpose of the study is to derive measures of susceptibility, resilience and exposure and in doing so explore some wider research questions. Firstly, is it possible to discern specific vulnerability pathways, or areas where a settlement is more or less likely to be critically affected should a flood occur? Secondly, is it possible to derive a vulnerability 'profile' and associated flood risk counter measures?

Systems Method

Background

The systems method is called an Abstraction Hierarchy (AH). Abstraction refers to "qualities of objects, events, phenomena etc. which are considered separate or apart from the objects, events or phenomena themselves" (Reber, 1995, p. 3). Thus a chair, for example, describes a general class of object somewhat abstracted upwards from the specific chair that one is sitting on at this moment. Likewise, the end product 'respond to a flood' is even more abstracted from the emergency responses and myriad other interventions that comprise a flood response. In either case, a form of hierarchy is implied in that 'concrete' physical entities will tend to reside at the bottom, contributing to progressively higher levels of 'intangible' abstraction higher up. Rasmussen (1986) and colleagues have developed a particular form of AH that relates well to the combined human and technical interventions involved in flood events, one that can be applied to systems of any size or type, as shown in Table 1:

Table 1 - Five levels of abstraction that can be applied to any system (Naikar et al., 2005)

There are many ways different levels of abstraction that can be derived. In this case, the five levels are based on studies by Rasmussen and colleagues into decision-making, and how humans think and reason about complex systems (Rasmussen, 1974: 1986). It was discovered that people reason about 'concrete' physical information (i.e. "how does this work") and 'intangible' higher level functional abstractions (i.e. "why is this here?" Jenkins, et al., 2009; Rasmussen, 1986) and this is what the links between levels of abstraction represent; the 'how' and 'why', or the 'means' that a system can use in order to achieve defined 'ends'. From a systems point of view, linkages between levels of abstraction are as important as the entities themselves, and this is captured in Rasmussen's AH through the use of 'means ends links' within a hierarchy, as shown in Figure 2.

Figure 2 – The generic form of Rasmussen's Abstraction Hierarchy has five levels of abstraction, with objects, activities, effects, outcomes and end state(s) joined by means-ends relationships (Jenkins et al., 2009). The example shown is that for a domestic central heating system.

Figure 2 presents the example of a domestic central heating system. While most people will be familiar with the 'physical objects' this system is comprised of; the radiators, hot water cylinder, thermostat etc., many will not think and reason about the system in terms of how these contribute to higher level functions. Indeed, what these higher-level functions actually are. The radiator, for example, serves the obvious function of radiating heat, but it also contributes to the transport of the coolant around the system, responding to pressure changes in the system (via associated pressure relief valves), and the control of radiated heat via the valves or radiator thermostats. These in turn contribute to higher level generalised functions such as 'heating domestic spaces', success in which can be assessed by the extent to which it contributes to values and priority measures like 'supply of radiated heat' but also other measures such as 'ease of installation' and 'ease of use'. All of these, in turn, contribute to the reason why the system exists in the first place, which is, among other things (such as system safety, cost and efficiency), to simply "match ambient temperature to lifestyle". Working from the bottom of the hierarchy upwards in this way enables the system to be thought about in terms of 'what' objects and functions exist, 'how' they support higher-level functions, and 'why' they do so. It is also possible to work from the other direction because the links are bi-directional. Instead of asking what-how-why, one instead asks why-how-what: why the system exists, how it functions, and what supports those functions, or indeed, what could support those functions. After all, the functional purpose of a central heating system could be met by a gas fired boiler supplying heat to water which is then pumped around a circuit containing radiators, or it could be provided by heating air and pumping this into the living spaces, or indeed some other form of technology not yet devised.

Rasmussen's AH enables any civil engineering system to be represented at any level of granularity (Stanton et al., 2006). As a method for exploring such systems it becomes possible to insert (or remove) concrete physical objects from the bottom of the hierarchy, and to analyse the effect in terms of higher-level intangible activities, effects, outcomes and end states. The approach is flexible. It becomes possible to analyse how changes at the bottom of the analysis, however small, might propagate up through the system to become magnified (or attenuated) at higher levels of abstraction. The means-ends links in the AH are an expression of all the 'affordances' in the system, or the 'possibilities for action'. Some of these will be readily apparent, while others will be emergent properties. Using the AH representation these possibilities for action become visually manifest and can be explored. This is a particularly relevant question when civil engineering systems (such as towns) are subject to disturbances (such as flooding).

Procedure

Step 1 – Four candidate towns in Scotland were selected: Dumbarton, Dumfries, Stranraer and Moffat. Scottish Environmental Protection Agency (SEPA) flood maps were accessed for each area, showing the flood extent for a 1 in 200 year fluvial flood event.

Step 2 – Classes of 'physical object' that fell within the borders of the indicated flood fluvial extent were extracted. These included objects such as private housing, shops, infrastructure (e.g. roads, gas holders, bridges etc.), industrial units, factories and so on. These represented the 'physical objects' affected by the ingress of a flood and the bottom level of the Abstraction Hierarchy.

Step 3 – The top level of the AH describes the system's 'Functional Purpose' or the systems' fundamental 'reason(s) for being'. In this case the Functional Purpose of a town was defined as:

1. Meet housing/accommodation/shelter needs
2. Support economic activity
3. Provide safety and security
4. Protect cultural heritage
5. Support freedom of movement (people and goods)
6. Provide infrastructure needs (power, water, waste disposal etc.)

Step 4 – Values and priority measures represent the second layer of the AH. They describe criteria that can be used to measure progress towards the Functional Purposes. Indicators used in the established parametric method (Flood Vulnerability Index; Balica et al. 2009) were used to populate this layer and linked to the achievement of Functional Purposes at the layer above. The rationale here is to use an established method for flood vulnerability assessment and embed it in the systems method.

Step 5 – Object Related Processes describe the capabilities and limitations of the physical objects in the system. They represent the next level of abstraction, showing the specific 'functions' to which physical objects (or groups of objects) contribute. Likewise, the middle layer in the AH analysis, Purpose Related Functions, raises the level of functional abstraction further still by defining the 'generic functions' that a town performs, as supported by Object Related Processes (in the layer below) and measurable by the FVI's (in the layer above).

Step 6 – Once the 'nodes' in the AH were inserted, the 'means-ends' links between levels were established. In this analysis the links represent the means-ends relations "that are evident in a particular situation or set of situations" (Naikar, 2014, p. 105), specifically, those likely to be in place prior to and at the onset of a flood. These were established by asking three independent analysts to complete the means-ends linking task according to strict 'linking criteria'. Any node in the Abstraction Hierarchy can be taken to answer the question of 'what' it does. The node is then linked to all of the nodes in the level directly above to answer the question of 'why' it is needed. It is then linked to all of the nodes in the level directly below to answer the question 'how' this can be achieved. For each town, an inter-rater reliability analysis was performed using Cohen's Kappa to determine consistency between observers. The kappa values for Dumbarton ($\kappa = .64$, $p < .0001$), Dumfries ($\kappa = .753$, $p < .0001$), Moffat ($\kappa = .651$, $p < .0001$), and Stranraer ($\kappa = .658$, $p < .0001$) indicate that for all four towns, inter-rater agreement was "substantial" (Landis and Koch, 1977).

Step 7 – The completed Abstraction Hierarchies were then subject to a numerical analysis based on Graph Theory. The constraints represented at each layer became nodes, and the means/ends relations became links. By these means the visual complexity of the raw AH diagrams was reduced into a tractable set of metrics which have underlying construct validity in relation to the vulnerability of the 'system' (i.e. the town in question). These metrics are described in full in the results. To anchor the results a baseline condition was created by 'fully connecting' an AH. This sets the upper limit for the various metrics that will be applied and allows comparisons to be made against an objective baseline.

Figure 3 – High level overview of the Abstraction Hierarchy (AH) for the town of Dumbarton showing the size and extent of the full analysis. This high level complexity is reduced by applying techniques from Graph Theory, which use the complex web of interconnections to define specific critical objects as shown in closer detail within Tables 2, 3 and 4.

RESULTS AND DISCUSSION

Critical Flood Risk Nodes and their Interactions

The Abstraction Hierarchy can be used to identify which nodes, and at what level of abstraction, are more or less critical when subject to a flood induced disturbance. Criticality refers in this case not to a value judgement concerning the node's physical role in a town, but to its functional role within a network in terms of affording or constraining behaviours within it. These might be 'common sense' nodes that arise from an intuitive understanding based on simple cause and effect logic (e.g. a gas holder sounds important and, for Dumbarton, is important), or they may also be 'emergent' properties arising from the complex systemic nature of the system (e.g. leisure facilities do not sound important but in Dumfries they were). The technique used to identify critical nodes within the Abstraction Hierarchies is to apply a graph theory metric called Sociometric Status, which is given by the formula:

$$\textit{Sociometric status} = \frac{1}{g-1}\sum_{j=1}^{g}(\chi ji + \chi ij)$$

where g is the total number of nodes in the network, i and j are individual nodes, and χ_{ij} are the number of links present between node i and j (Houghton et al., 2006). Network metrics of this kind are numerous (e.g. Monge & Contractor, 2003) and future work is aimed at exploring the construct validity of further variants. Sociometric status, however, serves as a valid starting point in that a) it provides an indication of the positional centrality of the node in the wider network, in particular, its ability to influence other nodes. Also b) it is compatible with the bi-directional nature of the means-ends links. Table 2 summarises the results obtained by applying this network metric to the AH analyses.

Table 2 – Top three nodes at each level of the Abstraction Hierarchy. The sociometric status values are expressed as a percentage of the maximum value (i.e. that derived from a fully connected Abstraction Hierarchy)

Table 2 identifies the top three critical nodes for each of the four candidate towns at different levels of the abstraction hierarchy. Two key observations can be made. The first is a wider point about how the differences between towns become progressively more 'damped out' the higher one progresses up the levels of abstraction. Specifically, the configuration of physical objects, and how they are affected by a flood event, cause individual vulnerabilities at the (lower) level of object related processes, yet the ability of all towns to meet their highest level functional purposes are affected similarly. To clarify, this does not mean that all towns are identically affected in flood extent or damage but that the extent and damage degrades the housing/ accommodation/ shelter function to the greatest degree when the system as a whole is considered. This is certainly consistent with recent flood events in the UK and the response hierarchy of responding agencies (e.g. Hartwell-Naguib and Roberts, 2014). Table 3 rank orders all of the higher-level systemic effects and also maps them onto the UK Environment Agency's response hierarchy of 'people-property-land'. The systemic insights discovered in this analysis map well on to the existing hierarchy, with the emphasis on people, then property, quite clearly manifest.

Table 3 – Order of criticality/priority of highest level Functional Purposes

The order of criticality of these functional purposes can be correlated to the type of flood damage or impact felt. The top three critical functional purposes can be categorised as direct impacts of floods, while the lower three are representative of indirect impacts (Carrera et al., 2015). The observed correlation reflects the severity of the impact, whereby impacts to housing, accommodation, safety and security, and freedom of movement are of great importance, and are often significantly impacted during and in the immediate aftermath of a flood event. Indeed, in terms of flood response this tends to be the first and immediate response of any government. This can be seen clearly in the case of the 2013/14 floods in the UK, where the Environment Agency delivered a hierarchical response to the population (people, property, then agricultural land) (Hartwell-Naguib and Roberts, 2014 as shown in Table 3). In reflecting not just this response hierarchy, but also the hierarchy of direct and indirect effects, the AH seems to be exhibiting good construct validity. Further analysis and development of the method to incorporate more complex functional purposes may prove interesting. For example, it may be of interest to test whether tangible or intangible impacts are more critical to the network. Likewise, the current analysis shows only the immediate effect of the flood, but future work will examine the temporal aspects.

Specifically the ability of critical functions to restore themselves to pre-flood levels depending on the recovery levels occurring elsewhere in the wider system.

Whilst the Abstraction Hierarchy performs as a common model applicable across all towns at the level of Functional Purposes, at the level of Object Related Processes more localised, functional degradation is evident (Table 2). There is some uniformity, to the extent that individual processes appear consistently across all towns (e.g. the provision of housing services), but there are also some important differences (e.g. cultural heritage is degraded by a flood in Dumfries to the same extent that education is degraded in Moffat). Again, the list can be read as a form of flood-degradation priority/criticality list. This analysis identifies the services particularly vulnerable within a studied area, and highlights these in a way which may be overlooked by more traditional methods. This is particularly true if multiple geographical areas are assessed in a consistent manner, which is conducive to the approach, as comparisons between results will highlight competing vulnerabilities.

Vulnerability Profile

A systemic feature of the results so far is the extent to which changes at lower levels of the AH become progressively damped out as they propagate upwards, in line with the critical functions degraded in real floods. A practical outcome of the work is that a vulnerability profile can be created, one that relates to a class of Scottish town similar to those modelled in this study. To do this, the Values and Priority measures are used. These are based on FVI metrics developed by Balica et al. (2009) and they belong to three vulnerability classes as shown in Table 4. Like all nodes in the AH the Values and Priority Measures have an associated Sociometric Status value. It is again possible to derive a value based on the percentage difference in Sociometric Status values between a fully connected AH (the 'control' AH described above) and those relating to real-life locations. Because any differences between real-life locations have been damped out at this level of analysis, only one set of values need be displayed in Table 4.

Table 4 – Each FVI / Value and Priority Measure has an associated Sociometric Status Value (shown as a % of the maximum value) and belongs to one of three vulnerability categories

A mean for each category of vulnerability can be derived (as shown in Table 4) which can then be used as a coordinate along separate axes described by resilience, susceptibility and exposure. The axes intersect to create a 'vulnerability cube' and the mean values provide coordinates to fix a point in this space (as shown in Figure 4).

Figure 4 – The coordinate space created by the intersecting resilience, susceptibility and exposure axes can be populated with the case study example(s). The coordinate space is divided into eight 'octants', associated with each is a distinctive flood response strategy.

If the coordinate space shown in Figure 4 is divided into eight zones (as shown) it can be seen that the modelled towns fall into a distinctive region. They measure low on exposure but also low on resilience and high on susceptibility (Zone 6). The eight zones create a form of taxonomy, which in turn represents the flood risk 'problem space' and where a given case study might fall depending on the structure and type of the associated AH, as shown in Table 5. This affords a different perspective and insight into the flood vulnerability of Scottish towns and perhaps even vulnerability in the UK. What is interesting is that the towns studied do not have a significant risk associated with flood exposure, but that their high susceptibility and low resilience increases their vulnerability. Traditional approaches to flood risk management tend to focus on direct impacts and addressing exposure issues. What this research highlights is that susceptibility and resilience may be at least as important in the Scottish, and potentially the UK context. This reflects current thinking in flood risk management which promotes a focus towards a more 'systematic' user/human orientated approach. Consequently this poses the challenge of identifying interventions that move these towns from Zone 6 to Zone 1 (Table 5).

Table 5 – The vulnerability problem space

Looking at recent UK events and the subsequent responses in a very general and simplistic way we can perhaps identify the impacts of current flood response on the UK. For example, the Association of British Insurers (ABI, 2010; UK Parliament, 2015) reported a significantly lower insurance payout (£500M) as a result of the 2013-14 flood events when compared to the 2007 events (approx. £3B). This is, in part, due to the impacted population being of a smaller number, and in a rural rather than urban location. However, the public perception of the 2013-14 events is that they were at least as bad as those experienced in 2007. Significant capital investment has been made in these intervening years, focused primarily on reducing exposure. This may have had an impact on the numbers of those directly affected, although comparison is not possible due to differences in type, location and nature of the events experienced. At a high level this would fit the profile identified above of low exposure, but high susceptibility and low resilience. In other words, having tackled the former issues of exposure, the latter issues of susceptibility and resilience seem to require greater attention, and this is a feature which emerges from the present analysis.

CONCLUSION

Flood vulnerability is a key issue, but there are still conceptual and methodological problems if the concept is to prove useful in informing policy and practice. Drawing on existing literature, this paper offers a working definition of the term, and relates it to three underlying concepts: susceptibility, exposure and resilience. The current state of the art is to use numerical measures and indices to show how catchments and settlements compare and where best to direct resources. In this paper we present an argument to suggest that susceptibility, exposure and resilience are emergent outputs of a complex, non-linear sociotechnical system. To make further progress a more systemic method is required in order to understand the critical interactions and what they mean for a place's flood vulnerability. The approach adopted in this paper is based on constraints and the idea that by modelling these constraints we create the 'behaviour space' of a place, and can begin to make sense not only of the behaviours which do occur, but also those behaviours which 'could occur' in major flooding episodes. By looking at the problem from a systems perspective the adaptability of the 'system' (i.e. the place) can be modelled and quantified to reveal a vulnerability profile, and a position within a typological flood risk model defined. Depending on the region a place falls within the typological model also depends the strategy for improving vulnerability in that location.

The model presented here identifies some interesting discrepancies between what we currently do to mitigate flood risk and what we potentially should do. The UK has tended towards management measures that focus on reducing exposure. The results of this model suggest that addressing urban resilience and susceptibility are at least as important, and this poses the question of how best to address them. For example, what interventions are necessary to improve our current level of vulnerability, and what can we learn from other international examples (e.g. Bangladesh, Vietnam etc) to improve our resilience and lessen our susceptibility? Using the structured approach proposed here, a methodological approach to testing interventions may now be possible.

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