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Decision-Support Tool for Retrofitable Flood Resilience

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Abstract

Flooding is an increasingly global challenge due to climate change and development practices. It can also be devastating to those affected. In the United Kingdom, it is projected that the number of people at high risk of flooding could rise from 1.5 to 3.5 million by 2080. Currently 400,000 homes and 75,000 businesses in England have an annual chance of flooding.

Therefore, the Environment Agency provides useful information on flood risks for a given location. This information is supported with different guides by the local Councils on how to prepare for, and get help during flooding. What remains unclear and easy to access are customisable retrofit actions based on local flood risks, necessary for an individual or household to implement anticipatory retrofit actions, thereby improving the resilience of their homes.

With this in mind, and knowing that studies about flood impacts focuses more on new construction or infrastructure solutions, this study aims to provide a tangible solution to raise the awareness of people living in a flood area about the level of risk they are exposed to, and to aid decision-making about effective preventive solutions specifically designed for their house, in an autonomous way.

The output is a decision-support tool developed to consolidate information about flood risks and present customised retrofit measures. The tool refers to the notions of damage and vulnerability of private housing to inform its operational diagnostic methodology. The output is a "to do list" of retrofitable work to increase resilience of the house against flood. 40 potential users evaluated and delivered positive feedback on the usefulness and functionality of the tool to raise awareness and improve resilience action. Future studies aim to fine-tune the tool and scale up the study.

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1. Introduction

Flooding, an increasingly prevalent global natural disaster, is predicted to occur more and more due to climate change [1]. NatCatSERVICE (2015), a natural catastrophe loss database which currently records about 1,000 events each year [2], states that flooding is one of the biggest and costliest natural disasters across the world. From their analysis from 1980 and 2015, the biggest flood event cost £32M in the United Kingdom.

Studies have estimated that the number of people at high risk from flooding could rise from 1.5 million to 3.5 million by 2080 [3]. Around 400,000 homes in England were subject to river and coastal flooding in 2015 due to their location.

Flooding is also a debilitating experience for those affected leading to extensive economic and social impacts. It destroys homes generating short and long-term consequences for everyone concerned. In addition to the security of people, which remain the principal matter of concern, property damages and rehabilitation costs can be extremely high, as well as rehabilitation delays for buildings. However, most of the population remain fully unaware of their vulnerability towards the risk of flooding [4]. Furthermore, despite extensive research on how to resist this natural catastrophe and the measures taking place for more resilient structures, a clear majority of existing construction techniques are still unsuitable for the risk of flooding [5]. It is therefore essential to work on flood prevention at an early stage, by establishing a method of diagnosis of the vulnerability of buildings and to propose clear adaptations designed to bring back security in private houses and make them reusable as quickly as possible.

1.1. Aim, objectives, context and scope

Current studies address various protected measures and their efficacy to make new houses more adaptable to flooding. This research focuses on retrofit opportunities to aid resilience of existing housing.

The aim of this project is to investigate an innovative survey and decision-support toolkit that can be used by homeowners and residents. The toolkit is fashioned to increase awareness and promote anticipatory protective measures based on the levels of risks to various building elements and functions. The guiding principle is that the proposed solution should lead to a better level of safety of the occupants of the building, a reduction of damages to structural and non-structural elements which would decrease the time to return-to-normal occupancy of the house after the flood.

To do so, the objectives of the research were:
- To investigate the current flooding risks to existing housing based on a specific type of flood in a chosen region
- To develop a suitable methodology for diagnosing the vulnerability of the building to flood risks
- To utilize existing case studies to specify the most relevant protective measures to the identified hazard
- To embed findings within a decision-support tool and evaluate its effectiveness and usefulness for increasing awareness, and retrofit action against flooding.

The two factors for assessing the impact of physical flood resilience at the micro scale are: flood characteristics and property characteristics [4, 11]. Due to the large number of protective measures for different types of building and floods, the scope of this study is further limited to a specific type of flood and a designated flood region in Bath, UK.

Bath is situated in a flood risk zone along the river Avon. Based on a 1 in 100 annual probability, 930 properties were at risk in 2014 [6]. In 2015, the number had significantly reduced but still counts to over 500 properties at risk from flooding [6]. The Environment Agency has set three zones depending on the level of risk of flooding (Fig. 1). The region is also considered likely to be impacted by climate change. The predictions expect an increase of the 1% AEP (Annual Exceedance Probability) in a 100 years' time but this will have no impacts on this study [7].

For simplicity, the study considers that:
- Zone 1, the risk is too low to be considered. The annual probability is under 1 in 1,000.
- Zone 2, has a medium probability between 1 in 1,000 and 1 in 100, the maximum water level in the habitats will not exceed 0.5 m and the duration of flooding is less than 2 days.

- For Zone 3, has a high probability over 1 in 100, the water level may exceed 0.5 m and the duration of flooding may be longer than 2 days.
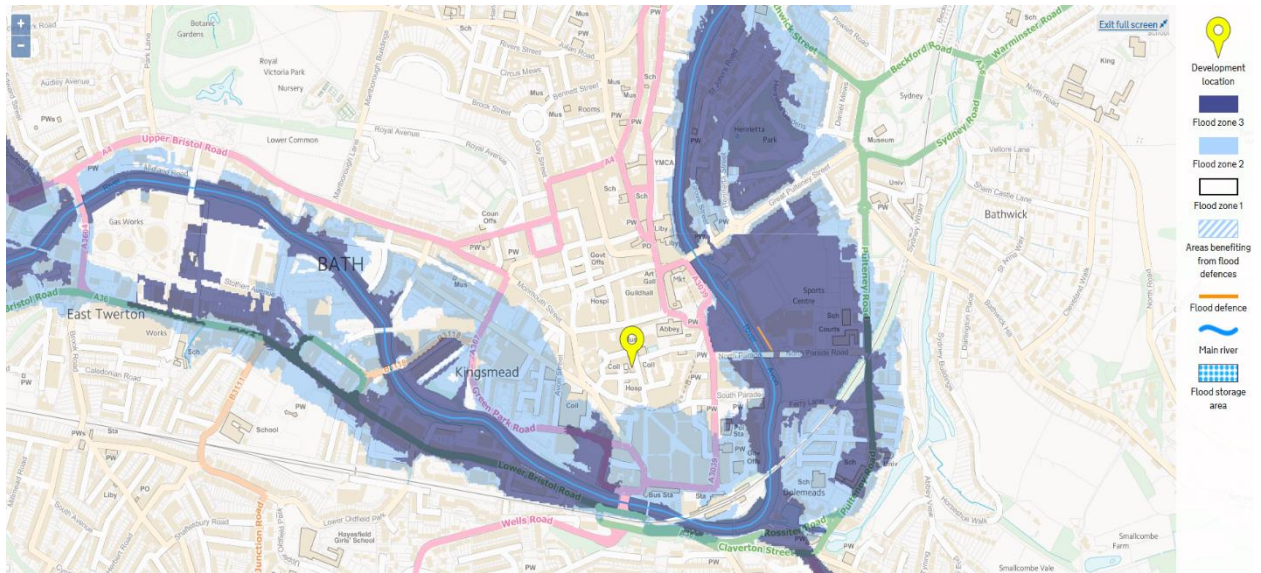

Figure 1 - Bath predicted flood zone [6]

The following conditions and limitations apply:
- The recommendations proposed in this document have no regulatory value. The technical elements of the works listed in this document do not replace the requirements of a prevention plan of the risks, technical standards or professional rules.
- This study does not assess the cost of potential damage and of the measures that would reduce vulnerability. The analysis is essentially focused on the safety of people and the return to normalcy of the building.
- The use of this tool cannot engage the responsibility of the organizations which contributed to its drafting nor of the professionals consulted for its elaboration.

2. Methodology

2.1. Methodological parameters

The parameters that informed the methods and outputs of the toolkit were broadly categorized as: vulnerability and impact. The vulnerability of a building to the risk of flooding is measured by the risk and exposure of a building, associated factors and functions to consequential damage as a direct or indirect result of the event. The actual amount of flood damage of a specific flood event also depends on the vulnerability of the affected socio-economic and ecological systems [8]. Vulnerability has been characterized using physical/tangible and non-physical/intangible metrics (Fig 2a.) as related to buildings e.g. structural and non-structural [9] material and personal health and safety etc. Vulnerability can also have a domino-effect i.e. the flooding of a site can create a succession of damages and inconveniences on buildings located nearby, and legal liability may be incurred [8]. It also affects the time taken to 'return to normal' - measured as the time elapsing between the event "flood" and full recovery - the moment when the activity in the building may satisfactorily resume. Although, it has been argued that recovery, then, does not necessarily constitute a 'return to normal [10]. In physical terms, this period may include cleaning and drying time as well as the duration of the restoration work if necessary.

Flood impacts are also typically classified as tangible i.e. monetary or economic terms, or non-tangible e.g. loss of life, health, well-being; or according to types i.e. direct or indirect and degree of damage [11]. There is some

disagreement in the literature as to the precise nature of the distinction between direct and indirect losses [11] e.g. Messner et al. According to [12], direct damage is usually measured as a damage to stock values, whereas an indirect gives the example that impacts on infrastructure can be classified as both direct and indirect. For example, floodwaters can directly damage infrastructure elements such as electricity substations or railway links. Failure of these elements can lead to indirect impacts in the wider system.
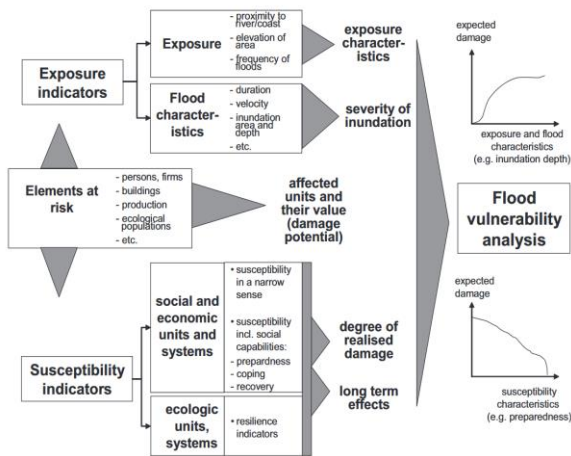

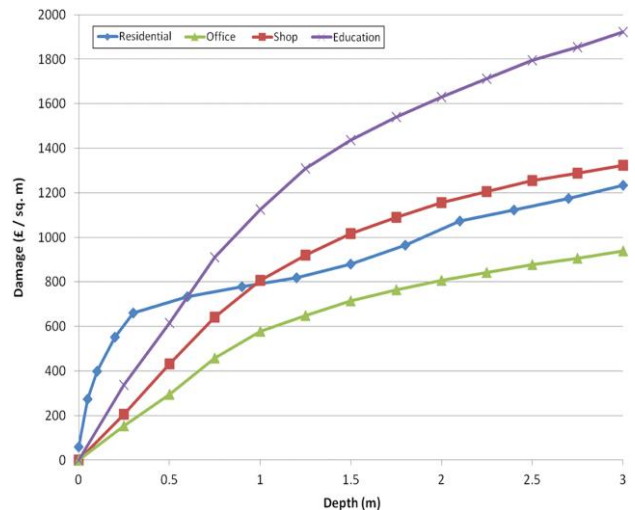Figure 2a - Indicators to be used in flood vulnerability analysis [8]

Figure 2b - Typical depth-damage functions (adapted from UK Multicoloured Manual (Penning-Rowsell et al.2005) in [11]

This project focussed on the physical vulnerabilities and impact of flooding on a building. Most building materials will deteriorate, at different rates, with prolonged contact with water. So factors including the water depth (Fig. 2b), the duration of immersion, and the flood rise rate (flow velocity), the turbidity and the transport of contaminants are important when exploring building impact [4, 11]. The degradation of materials is also impacted by the duration of contact with the water. The longer the flood, the more the diffusion of moisture in the walls by capillary phenomena, leading to swelling or hydrolysis. As with water depth, the relationship between the immersion time and the magnitude of the damage is not linear. It evolves in stages with specific building thresholds. Taking gypsum board for example, the immersion time of: Less than a day has 20% chance of damages; 2 to 3 days has 50% chance of damages; More than 3 days equated to 100% chance of damages [13].

2.1.1. Criteria for tool development

The case buildings are masonry houses situated in Bath Zones 2 and 3, with flood characteristics specified as: flood height of more than 1m [14]; flood duration below or exceeds 48h. The toolkit development was approached in two stages: 1. Identify vulnerability: consider conditions within the specified flood zone and identify potential risk to defined parts of the building, and 2. Minimise impact: using either a resisting or yielding strategy.

For simplicity, the tool combines the strategy of resisting for habitats in zone 2, whose characteristics of the flooding are coherent such as the height under 0.5 m and the duration under 2 days. Conversely, the tool combines the strategy of yielding for houses in zone 3.

Two main strategies can be used to reduce building vulnerability and minimise damage due to flooding. These are 1. resisting strategies e.g. sealing and installing barriers and 2. yielding strategies as water cannot be prevented indefinitely from entering a building.

User input is required for selecting options and choices e.g. the list of previous damages and outputs are given as the most relevant/customised retrofit work to reduce the vulnerability of the building. The outputs are presented in varying levels of effectiveness depending on the objective to be achieved e.g.: Occupant safety; Reduction of the time to return to the dwelling and; Reduction of damages.

The user however does not have the option to choose an objective. To select the relevant measures, it is necessary to check the suitability of the works with the specificities of the housing (e.g. not to secure swimming pools or lifts if the house does not have them). This step allows the individual to quantify the solutions and to have his strategy defined.

3. Toolkit: inputs and outputs

3.1. Stage 1: Defining the flood scenario

The objective here is for the tool to define the characteristics of the flood directly relevant to the user's place of residence. So the tool allows to directly obtain the flood zone by clicking on the map of the city of Bath (Fig.3).

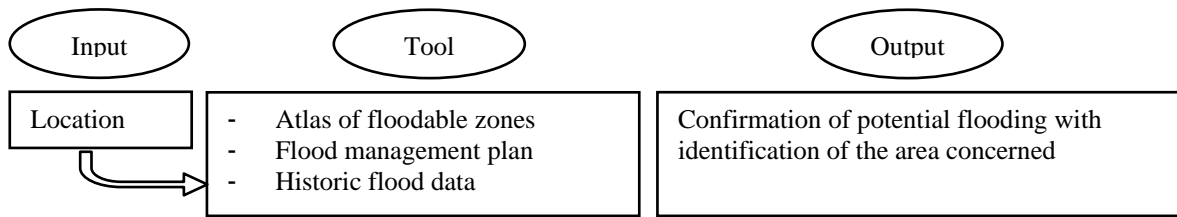| Input	Tool	Output
Location	- Atlas of floodable zones - Flood management plan - Historic flood data	Confirmation of potential flooding with identification of the area concerned

Figure 3 - Defining the flood scenario

From the existing data, the tool indicates additional information on the characteristics of the flood to the user: Flood level; Duration of the flood; Duration of the warning before the event and; Duration of help after the event

The last two options are not directly relevant because the info of the zone is sufficient for the objective of the tool by means of the simplifications described in the methodology.

3.2. Stage 2: Assessment of damages

The flood impact or damage is informed by the characteristics of the building [11]. The evidence informing this stage of the tool are provided by [15, 16, and 17]. These are translated as a simple checklist for user input. Based on this, the tool automatically evaluates the potential damage as a function of the flood zone to which the flooding characteristics corresponds and the characteristics of the building. The next input of the tool therefore is to select the parts of the building existing in the dwelling and how they are made through a pre-selected checklist (Fig 4.)
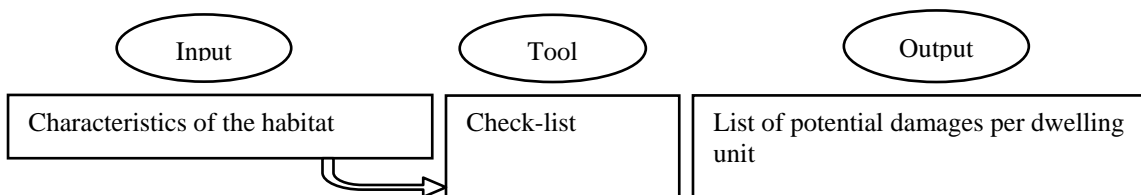
Input	Tool	Output
Characteristics of the habitat	Check-list	List of potential damages per dwelling unit

Figure 4 - Assessment of the potential damages

3.3. Stage 3: Assessment of vulnerability

The vulnerability of a building to flooding is measured by the degree of damage to the building, its occupants and content [8]. Defining the vulnerability is based on two possibilities: if the impacts can lead to the danger of human life, and if the impacts increase the time required to return to normal operation of the building following the flood event.

3.3.1. Vulnerability related to personal safety

The characteristics of the building that make people vulnerable to physical harm is explored at this stage, paying attention to:

- The capacity of the building to withstand the exceptional stresses due to the rise of water;
- The existence of an out-of-water zone;
- The risks associated with technical equipment (such as electrical);
- The risks associated with changes in the environment (collapses of materials, slippery soils, etc.).

To clarify the risk incurred by persons, a classification of vulnerability level related to their safety is established for each potential damage as per the following table [18].

Table 1 - The degree of vulnerability associated with the safety of persons

	Degree of vulnerability	Consequences of damage on the safety of persons
0	Null	No damage. No risk to the safety of persons.
1	Low	At the origin of a slight accident such as contusions, shock, minor sprains, etc.
2	Medium	Source of more serious accidents such as light fractures, etc.
3	High	Source of severe accidents or deaths.

3.3.2. Vulnerability related to return-to-normal

The return-to-normal depends on the importance of the damage to the real estate, on the structures and elements of the construction of the building, on the time required for their restoration, and on the restoration period of the utilities. Similarly as the personal safety, a level of vulnerability associated with the return to normal is established for each potential damage as per the following table [18]. The levels set out in Table 2 are technical delays resulting exclusively from reclamation work, without taking account of the time taken to award contracts and the release of financing, the availability of construction companies, etc. The assessment can be made by forming a hierarchy based on the gravity of the impacts.

Table 2 - The degree of vulnerability associated with return to normal delays

| Level	Degree of vulnerability	Consequences of damage on the return to normal
0	Null	No restraint to return to normal with delays of less than a few days.
1	Low	Necessary repairs make the building unavailable for a few days.
2	Medium	Necessary repairs rendering the building unavailable for a period of several weeks.
3	High	Necessary repairs rendering the building unavailable for a period of several months.
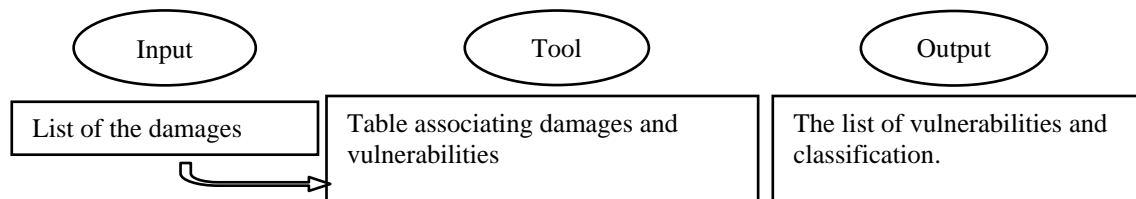
Figure 5 - Assessment of the vulnerability

The tool therefore displays the list of vulnerabilities associated to the inputs from the two first stages as judged against Table 2.

3.4. Stage 4: Identification of measures to reduce vulnerability

For simplicity, the tool combines the strategy of resisting for habitats in zone 2, whose characteristics of the flooding are coherent such as the height under 0.5 m and the duration under 2 days. Conversely, the tool combines the

strategy of yielding for houses in zone 3. Options for the resisting strategy includes: sealing gaps and waterproofing materials. The yielding strategy consist in letting the water enter the building, taking all necessary measures to limit the damage and reducing the time to return to normal. The tool displays the proposed work depending on the Zone selected (Fig. 6).
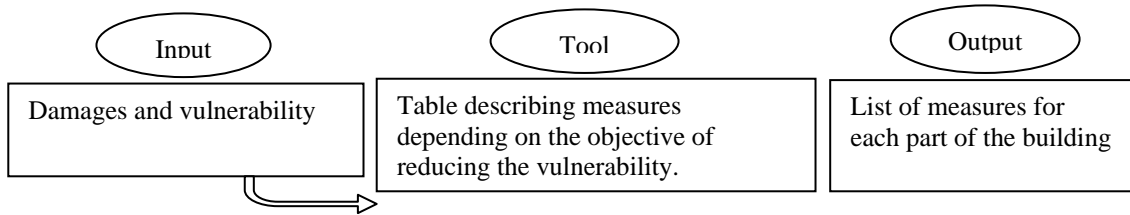

Figure 6 - Tool identification of measures to reduce the vulnerability to flooding

4. Toolkit evaluation

Forty people were randomly selected to evaluate the tool against criteria defined in a questionnaire. The participant's age were between 20 and 60 years old with an average age of 30. 20% are students, the rest were professionals. Less than 40% had experience of, or live in a flood-risk area. All live in houses built over 20years ago and are not designed or built to be flood resilient. The participants do not directly reside in the specified zones but were asked to evaluate the tool using the significant flood zones (2 and 3).

The tool was deployed to the participants via Dropbox and this caused a number of issues with participants not being able to effectively download and install the tool. It was found that these issues depended on computer configurations, anti-virus software, and the lack of access to Dropbox upstream and the lack of applications to unzip the file. All these operations were previously identified and solutions presented in the user guide. However, most of the participants did not consult the guide. This led to the conclusion that a more seamless and intuitive deployment e.g. through a web platform is required. The user satisfaction feedback was low due to this. But once the tool was made available, the ergonomics were considered satisfactory by 90% of users. The interactivity with the map on the first page, the possibility to go back and the colorization of the different degrees of the vulnerabilities were the most appreciated factors.

On tool presentation and content: the users all confirmed that the exhaustiveness, or vocabulary of the tool was not an issue. However, 40% of users suggested additional options to describe more precisely the characteristics of their home including a wider range of materials. This was predictable due to the limited choice of options to only probable and significant damage. On usefulness to raise awareness and promote retrofit action: 90% of the affected users understood the value of the work and were sensitive to the need to protect themselves from the risk of flooding, especially since the subject is currently topical. However, it was difficult to gauge the extent to which this will translate to actual retrofit actions. The other feedback that emerged are the need for illustrations of the damages and the recommended works (50%), and to improve the display size to better scale according to the screen size (40%) so that content and instructions are not hidden whilst navigating through the tool. More significantly, the need to include economic factors e.g. costs of proposed solutions was also highlighted by the majority.

5. Discussion and conclusion

A decision-support toolkit was proposed :
- To raise awareness of the level of risk of flooding in an existing dwelling based on the Environment Agency's real-time flood zones linked to the probability of the event (100 to 1000 years' floods).
- To encourage anticipatory action by homeowners or residents through preventive retrofit works instead of post-event repair.
- To provide a more specified, customizable recommendations of retrofit works based on locale and building type.

The evaluation stage of the project found that the proposed tool achieves better awareness, but a follow-on study is required to measure the degree of action taken as a direct result of using this tool. More specific to the functionality

of the tool, it was noted that the tool is sufficiently accessible in content and format for most types of users. However, the deployment problems means that it is important to explore alternative deployment formats including the web-platform option. There were user recommendations to improve the visual ergonomics/interface of the tool e.g. scaling of text and content to screen size etc. but the participants did not consider this a priority.

An important output of this study however, was the need to include non-tangible factors such as economics of damages, balanced against the cost of retrofit before flooding, as well as the cost of repair after flooding. The visualisation of this economies of scale could help to transcend the awareness-action gap. This aspect will be covered in the next stages of this work.

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