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and de Graaf

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Methods of assessing flood resilience of critical buildings

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An overview is presented of recent advances in the assessment methods and mitigation solutions for the performance of critical buildings during flood events. This draws on research focusing on critical urban infrastructure, which is defined as assets that are essential for the continuity of economic activities in cities and for the basic living needs of the urban population. These assets include networks as well as buildings, the latter (termed 'critical buildings') having an important role in protecting equipment and personnel associated with the networks. Examples include power stations, transport control centres, communication hubs, fire stations, shelters and hospitals. Unlike domestic constructions, due to their specificity, these buildings cannot easily be categorised in terms of type of construction or age, and have to be treated as individual buildings. Three methods are presented as a framework with a logical progression for the assessment of building flood vulnerability and the identification of improvement measures: the 'quick scan' method, the 'selection and evaluation tools for flood proofing of buildings' and the 'individual building flood damage tool' (IBT). It is expected that building owners, insurance companies, local authorities and agencies with urban flood management responsibilities will benefit from the application of the framework and tools presented.

1. Introduction

Increasingly severe and frequent wet weather events and higher population pressures have prompted an ever more encompassing range of methodologies and solutions for flood risk management aimed at protecting people and assets from the impacts of floods. A European-wide definition of flood risk management, developed and established during recent EU-funded projects such as Floodsite (2015), FloodProBE (2015) and Corfu (2015), is 'the continuous and holistic societal analysis, assessment and mitigation of flood risk'. Included in this definition are the analysis of flood risk on the one hand, and risk mitigation measures on the other, which are intrinsic elements in the search for effective solutions (Escarameia and Stone, 2013). Within the specific context of urban communities, Zevenbergen *et al.* (2010) have provided a comprehensive analysis of the urban aspects of flood management, integrating knowledge from a range of relevant disciplines, from hydrology to urban planning, and from sociology to architecture and construction. In the years since that publication appeared, further significant developments have taken place, focusing on specific aspects of urban flood risk management.

This paper introduces several assessment methods and mitigation solutions specifically developed to aid the understanding of how buildings perform during flood events and how their capabilities can be improved. It draws on work developed during FloodProBE and other recent European projects, with a focus on urban environments and critical urban infrastructure. Within the context of the project, critical urban infrastructure was defined as those assets that are essential for the continuity of economic activities in cities and for meeting the basic living needs of the urban population. As well as networks for energy and water/sewerage supply, transport, information and communication services, it includes the so-called 'hotspot buildings' (or critical infrastructure buildings) for their role in protecting equipment and personnel associated with those networks. Examples include power stations, water and wastewater treatment plants, control centres for public transport, communication hubs, fire stations, shelters and hospitals.

Buildings can be subjected to flooding from the whole range of flood sources – river, sea, sewers, groundwater and rainfall. Flood damage to buildings and their contents depends on a number of variables: event-related variables, such as over-floor water depth, flow velocity, rate of rise, presence of debris and contaminants, frequency and duration of inundation, and timing; and building-related variables, such as type of structure and construction, materials used and their drying characteristics, services and their locations, as well as the condition of the building prior to being flooded.

Much research has been recently undertaken to investigate the effect of floods on buildings, some concentrating on developing frameworks for urban flood resilience (e.g. Blanco and Schanze, 2013; de Graaf, 2012; Hu and Khan, 2013; Kienzler *et al*., 2013; Ogunyoye and Dolman, 2013), some on providing innovative technologies to prevent or limit the ingress of flood water into buildings (see e.g. the SMARTeST (2015) project), and some on the possible role that building materials can have in mitigating damage and speeding up the recovery process (Escarameia *et al.*, 2012) (Figures 1 and 2).

Various researchers have also developed flood-damage prediction methods for buildings, mostly covering residential buildings. Walliman *et al.* (2013) have presented a review of available estimation methods used in the UK, Germany, the USA and Australia, and suggested ways to improve on these methods in order to estimate damage to individual buildings, particularly non-domestic ones. The Flood Hazard Research Centre handbook (FHRC, 2014) and its more extensive companion manual (Penning-Rowsell *et al.*, 2013) are a source of information on new methods for estimating property damage, and give up-to-date depth–damage curves that include cleaning and drying costs for the UK context. Blanco and Schanze (2013) suggest a framework based on building classification, which was developed using remote-sensing data to establish roof surface as well as topological and building characteristics; selection of representative types of building then allows the assessment of their vulnerability in terms of depth–damage functions, which are defined based on the principal components of the buildings, such as floor height, building components and materials. With no intention to detract from the merits of the above methods and approaches, it is noted that these methods have been developed for the assessment of types of buildings to allow general decisions at a neighbourhood/city level. It can, however, be argued that a much greater level of detail is required when critical buildings are being considered: these buildings, unlike domestic constructions, often include several different types of construction within the same premises, and so characterisation according to construction type is insufficient (Walliman *et al.*, 2013). Until recently, no reliable method was available for anticipating and estimating post-flood remedial works, as well as proactive retrofitting, of buildings at an individual scale. Walliman *et al.* (2013) reported on an assessment methodology that identifies the likely level of damage to individual buildings, the results being expressed as the predicted costs of remedial works, and described a tool (the individual building flood damage tool (IBT)) for the detailed estimation of extent of damage. This allows plans to be developed in advance of flood events

Figure 1. Example of a masonry building during a flood

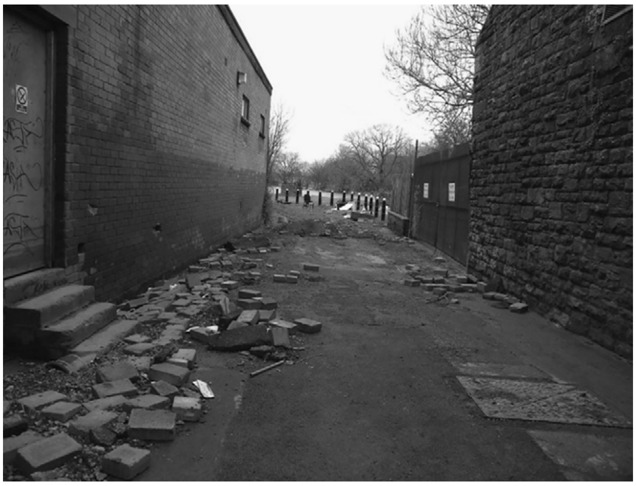


Figure 2. Debris from buildings (and pavements) after the passage of a flood

to ensure prompt rehabilitation of buildings, which are particularly relevant for critical infrastructure buildings.

The following methods, described in detail in the sections below, present a possible framework with a logical progression for the assessment of building flood vulnerability and the identification of improvement measures targeted at critical infrastructure (it is not advocated that all steps are necessarily followed, as this will depend on individual circumstances)

- the 'quick scan' method
- the 'Selection and evaluation tools for flood proofing of buildings'
- the IBT.

2. The quick scan method

Within an urban environment the number and type of flood vulnerable infrastructure elements is likely to be large and very varied. To facilitate action prioritisation, the quick scan method was developed (Zevenbergen *et al.* (2014) describe the application of the method to neighbourhoods in Bangkok, Thailand). The quick scan method is a rapid assessment and ranking procedure which identifies assets that are at most risk from flooding so that effective – but at the same time easily achievable and most cost-effective – interventions are put in place to alleviate the damage to these assets (these are termed 'low-hanging fruit' as they offer the 'easiest picking'). This pragmatic method is best applied to a neighbourhood or city district (rather than to whole cities, in view of their complexity) with a well-defined boundary based on parameters such as population density, geographic location or socio-economic status of the neighbourhood. Figure 3 shows the consecutive steps for application of the method.

- *Step 1 – Identification of critical infrastructure assets and ranking of criticality.* Assets, including both critical networks and buildings, and the relationship between them (i.e. dependence of assets on one another) are first identified. A network analysis is then carried out by describing the critical networks, studying the effects of failure of one element on the functioning of the network, the effect of failure of the network on other networks and ultimately the effect of failure of one or more networks on the community.

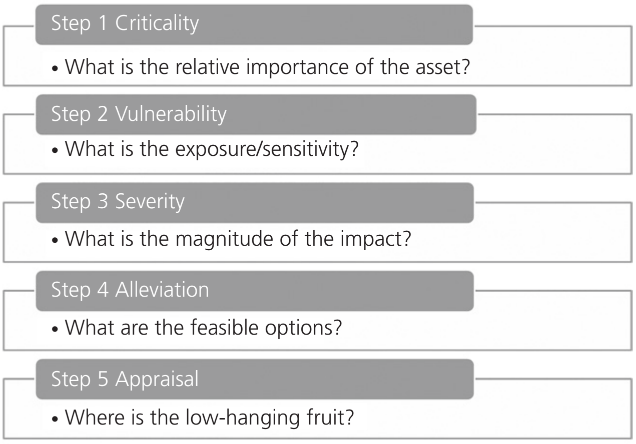


Figure 3. Steps in the quick scan method

- *Step 2 – Analysis of the exposure and sensitivity of the critical assets* (i.e. their vulnerability). Clear thresholds can sometimes be found that help define the sensitivity of elements (e.g. in Dordrecht, the Netherlands, transformer stations will fail if water depths exceed 0·3 m), and this allows analysis of potential flood parameters and probabilities (the 'exposure') to be carried out. However, not all cases have well-defined thresholds. Being the most readily available parameter, the main flood parameter is water depth, but flood duration and velocity may also be used. Flood exposure analysis is normally based on historical data and/or model simulation of potential floods, and the sensitivity depends on the flood resistance and resilience of the critical assets. Flood-resistant assets are those that can withstand a particular flood-water depth without damage or failure; flood-resilient assets are those that, when in contact with flood water, experience no permanent damage, retain structural integrity and can resume normal operation after the flood has receded. Vulnerability can be expressed in monetary terms or be based on indicators such as the duration of outage, the number of people affected or combinations of these.
- *Step 3 – Determination of severity of the impact.* This involves assessing the effect of failure of the assets (nodes and connections) on the delivery of service (first order); the effect of failure of a network (or part of one) or node on other networks; and the likelihood of failure (flood exposure and sensitivity).
- *Step 4 – Identification of options available to mitigate the effects of flooding and associated costs.* The options comprise flood proofing (resilient and resistant) construction (see Section 3) and retrofitting techniques, ranging from simple interventions, such as temporary closures, to permanent elevation. It is also possible to alleviate impacts from failure by reducing the criticality of the sensitive elements (e.g. by making the network more redundant in order to ensure that if one node fails the network will still function).
- *Step 5 – Identification of the 'low-hanging fruit'.* The sequence of previous steps leads to the identification of assets where actions can be undertaken at the lowest cost but with high impact. This can be taken as part of a wider range of interventions to fully protect the urban critical infrastructure.

3. Selection and evaluation tools for flood proofing of buildings

Flood proofing measures for buildings have been suggested by a number of researchers and have been published in guidelines in various countries in varying degrees of detail (see e.g. Vassilopoulos *et al.*, 2007; Escarameia *et al.*, 2012). Specific guidance for critical buildings and retrofitting are, however, more sparse, as are evaluation methods to assess the effectiveness of the measures. De Graaf *et al.* (2012) define flood proofing as measures that allow buildings to cope well with floods, the measures being (see also Escarameia and Stone (2013), and FloodProBE (2012a)):

- wet-proof construction – allowing temporary flooding of the lower parts of a building, the building materials being easily repaired or replaced
- dry-proof construction – preventing water ingress by the use of water-resistant materials and/or coatings
- raising the building, on stilts or mounds
- floating or amphibious buildings
- temporary flood barriers – only placed when a flood is expected to damage the building
- permanent flood barriers, specifically constructed to protect a building or group of buildings.

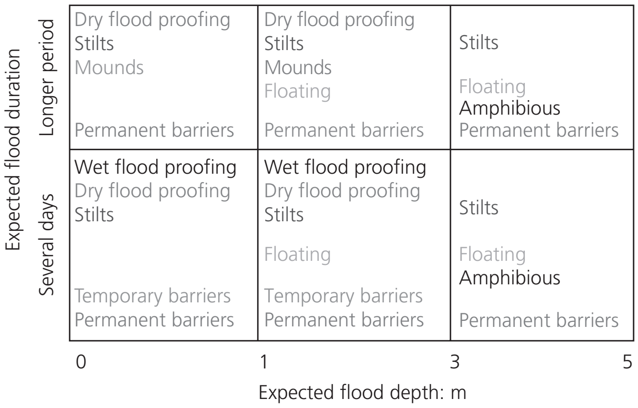
De Graaf *et al.* (2012) have also made recommendations on the applicability of the various concepts for the case of critical buildings (hotspots), and Figure 4 illustrates the dependence of the applicability of measures on flood depth and duration.

A spreadsheet model using Excel was developed incorporating three selection and evaluation tools to help designers and decision-makers choose the most appropriate flood-proofing concepts for buildings at different stages of the urban development process. Validation of this model was undertaken through three case studies and a pilot study involving different types of flood (coastal, riverine and pluvial) and building type. For each case study the flood event was defined in terms of frequency, depth, extent and rate of rise of the flood. The case studies and pilot study (where the application of the model was thoroughly tested involving all relevant stakeholders) were

- a hospital – the Memorial Medical Centre in New Orleans, USA
- a bank headquarters – the Cassa di Risparmio di Venezia, Venice, Italy
- an electricity substation – Walham substation near Gloucester, UK
- a hospital – St Francis Hospital, Rotterdam, the Netherlands (pilot study).

In the first stage of the process, when options are being explored, the relevance of applying flood proofing measures is assessed based on two parameters: the service area (i.e. how big an area/how many people rely on the service provided by the critical building (hotspot)) and the magnitude of the flood event (i.e. how many people will be affected). A relevance map (Figure 5) gives an indication of the relative importance of flood proofing a particular hotspot building based on flood impacts and the service area of the building.

In the next stage of the urban development process, when possible measures for flood proofing are considered, the selection tool helps narrow down the most feasible flood-proofing concepts based on information on location and building characteristics. This tool, by working at a qualitative level, still requires only a limited amount of information, but more information than is required in the first phase. In the decision-making phase, the evaluation tool acknowledges that finding the optimum solution (from both a technical and a cost viewpoint) is not easy because various parameters play a role, these parameters being related both to the properties of the building (site area/perimeter, building area/perimeter, land cost, height, service area) and the type and characteristics of the flood events (depth, frequency, flood onset time from time of warnings). The evaluation tool was developed to provide detailed (quantitative) information about the costs of several possible options for flood proofing a specific hotspot. Relatively detailed information on the hotspot (including whether it is a



Expected flood duration	0–1	1–3	3–5
Longer period	Dry flood proofing Stilts Mounds Permanent barriers	Dry flood proofing Stilts Mounds Floating Permanent barriers	Stilts Floating Amphibious Permanent barriers
Several days	Wet flood proofing Dry flood proofing Stilts Temporary barriers Permanent barriers	Wet flood proofing Dry flood proofing Stilts Floating Temporary barriers Permanent barriers	Stilts Floating Amphibious Permanent barriers

Figure 4. Applicability of flood-proofing measures according to flood level and duration

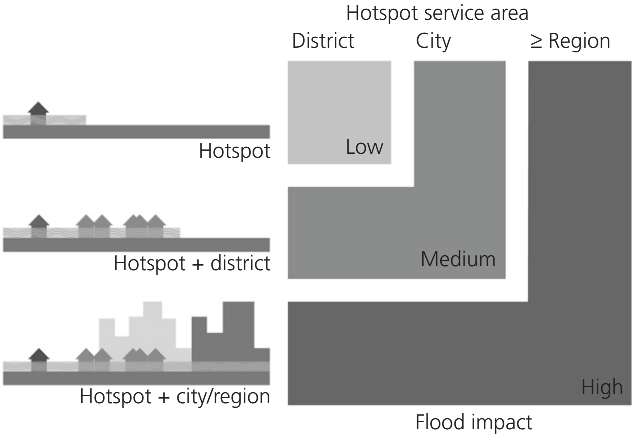


Figure 5. Example of a generic relevance map

retrofit of an existing building and whether the site is protected by levees), flood characteristics and location characteristics therefore must be available for the application of this tool. Figure 6 illustrates one of the most relevant components of this tool – the installation time (in this case of different flood barriers) – other components include the area required, the height range and cost.

4. The IBT

When considering critical (or hotspot) buildings, the variety of designs and constructions used makes it unrealistic to categorise them into meaningful types with regard to their vulnerability to flooding. In order to be able to predict the effects of flooding and the costs of reinstatement of these buildings, it is more appropriate to estimate damage at an elemental level (e.g. wall, apertures, floor, services) rather than considering the building as a whole. An assessment methodology has been developed (FloodProBE, 2012b) that distinguishes between buildings built using different construction methods and materials. It helps identify key risks in order for buildings to be retrofitted to improve their robustness against flooding, facilitates planning of rehabilitation response, and helps target investment for reducing future vulnerability. Although particularly relevant to critical buildings, it can be applied to other building types.

A prototype of the damage prediction tool (IBT) was developed based on the above methodology (Figure 7). The IBT is a simple to use tool and was designed to enable building professionals who have no specialist knowledge of the effects of flooding on buildings to predict the cost of flood damage to individual buildings depending on the nature of the flood event and the individual constructional characteristics of a particular building (FloodProBE, 2012b). IBT enables professionals to foresee the likely consequences of flooding and make a cost–benefit analysis of the different measures that could be undertaken to protect a building from these consequences. The tool is designed to be used by building professionals throughout Europe. Although the cost data are based on UK prices in 2012, conversion factors are built into the tool to make adjustments for the different building costs in other EU countries. The prices and the conversion factors can be updated regularly to reflect changes over time.

The tool is based on a spreadsheet, with a simple user interface that requires the user to insert the following basic information about the context

- name of the premises
- flood characteristics (flood depth (m), flood duration (d), pollution, velocity/debris – choices are given for values to these
- currency (£ or €)
- region (EU country) – a calculation is then automatically made for a regional adjustment (accounting for differences in building costs in various EU countries).

The next set of information required concerns the building itself

- building element – the choice is from external walls, internal walls, floors, windows, external doors, stairs, services and finishes, which are selected in turn and the following data for each is inserted
- type (e.g. choice for external walls is masonry monolithic, cavity wall, concrete, steel, curtain wall, timber)

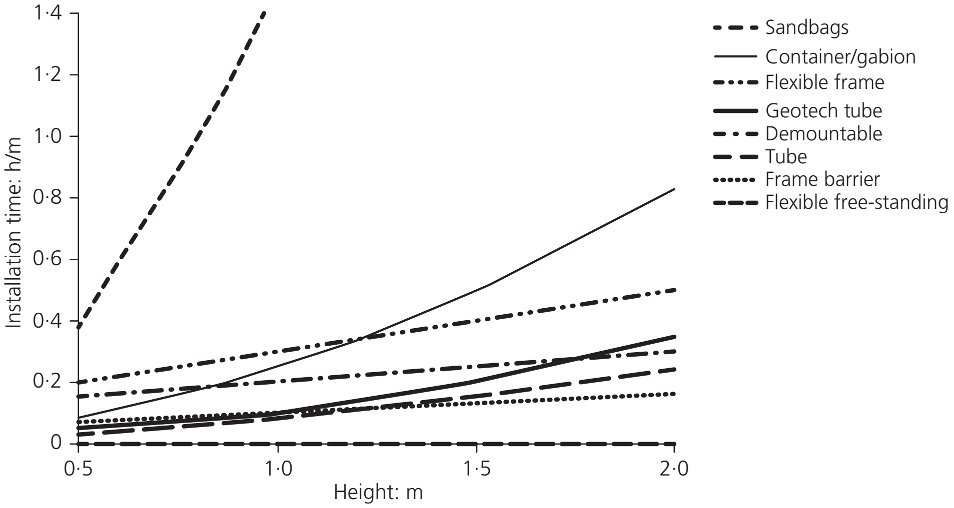


Figure 6. Example of installation times as a function of flood height required for different flood protection products

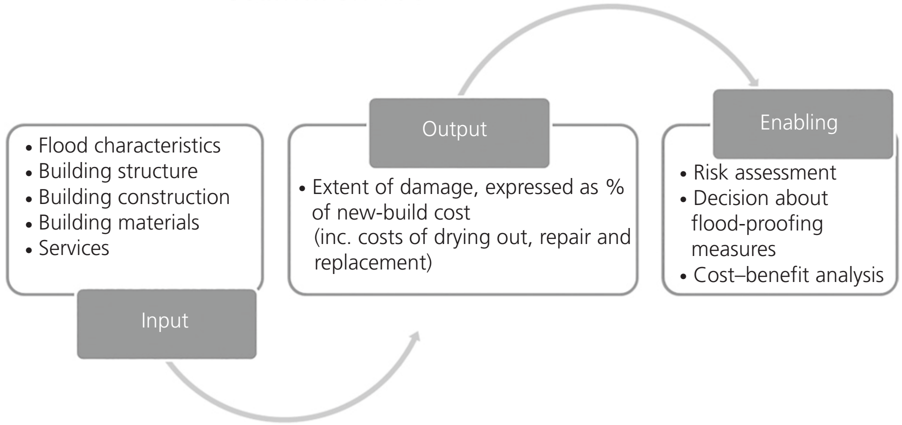


Figure 7. The IBT

- description (provides alternative specifications for the above choices)
- length and height in metres (or area in m^2 as appropriate) of the element (this needs to be measured from the building).

The tool then calculates the repair cost of the chosen element and adds the sum to a list. The previous process is repeated for all the affected elements, and when complete the tool calculates the overall cost of the building repairs. An additional cost element can then be added – that of mechanically assisted drying.

Accordingly, all the elements of individual buildings likely to be affected by flood water are included in the tool, namely the basement and foundations, the external walls, the ground floor, the internal partitions including the internal doors and joinery, the external doors and windows, as well as the associated services such as electrics, plumbing and ventilation. The actual cost of flood damage to individual building elements is calculated according to their construction and materials, the types of services and the nature of the flooding. The initial output, based on the database contained within the tool, predicts the cost of cleaning, repair or replacement, and is expressed as a percentage of the new-build cost of each element. Additional percentages are added for pollution clean-up and sterilisation and mechanically assisted drying. An approximate indication of the actual cost of returning the building to use, depending on where it is and when the flooding occurs, can then be produced by the tool when it is combined with calculations using the areas, lengths or numbers of affected elements and the current or predicted rates of construction prices. It should be noted that the way in which the flood depth is taken into account with regard to repairs of building elements depends to a large extent on the different approaches in each country and on different individual practices within a country. For this reason the tool is flexible enough to allow tailoring to the practices in each country.

Validation of the prototype tool was carried out using three case studies in order to gauge the accuracy of the predictions made by the tool. These were selected from data supplied by AXA Insurance on three premises that were flooded in 2007 in the Sheffield area of the UK. The data provided in each case consisted of a description of the flood event, an outline specification and photographs of the building, square metres of the floor plan, and the cost of remediation. Owing to the lack of detailed construction drawings, some assumptions had to be made about the exact details of the building construction and areas of elements. Entering the information into the tool was straightforward once these assumptions had been made, and the cost calculation was quickly produced.

The comparison of the tool's estimate of the costs of repair against the actual costs of the case study buildings resulted in a close match in two cases. The values for an engineering workshop and a wine store and warehouse matched with 88% and 95% accuracy, respectively, while the estimate for the third case study, an office building, was only 63% accurate. It was concluded that the latter poor match was due to insufficiently detailed building data (particularly about high levels of finishes) and damage cost data on individual constructions and materials. This indicates the need for further detail and refinement of the latter, and further testing of the tool using case studies for which a full set of construction drawings and specifications are available, as well as a detailed account of the nature and extent of the damage caused by the flooding.

Hence, it is noted that obtaining detailed information from real flooded critical buildings has offered some challenges due, in part, to commercial sensitivities, with the result that the validation of the tool was relatively limited. The prototype tool can therefore, at this stage, be regarded as a demonstration of the methodology for calculation of flood-damage costs based on flood characteristics, detailed constructional information and associated damage factors. It will provide a springboard for the development of a fully functional tool that can be used for buildings of all types throughout Europe. It is noted that, when assessing feasibility and viable flood proofing options for critical buildings, conventional cost–benefit analysis concentrating on buildings alone is not the most appropriate tool. It is important to consider indirect impacts that reflect the wider interdependencies of critical buildings and associated networks, but the calculation of indirect impacts is not considered to be within the scope of this tool.

5. Practical considerations

All the tools described in this paper require knowledge of building flood resilience but, owing to their simplicity, the tools can be easily used by relevant professionals.

Improvements in the building flood proofing tools can be achieved by including additional flood data parameters that are relevant (e.g. flood velocity and duration) but currently less readily available. Equally, inclusion of infrastructure networks that establish connections between hotspots would improve the quality of the flood proofing assessment. Cost data on flood proofing measures can be improved by consulting local suppliers. Location-specific data on costs, land value and other factors can be easily included in the building flood-proofing tools. While these tools cannot replace a detailed investigation of flood-proofing options at a specific location, they can be used to limit the available options and give an overview of which options should be investigated further.

The IBT relies on a range of expert assessments of the scale of damage and costs of repair/replacement of a wide range of building constructions. These assessments can be made more robust by repeated testing against real situations, both in the laboratory and in real-life flood events experienced in the past. This requires much more specific information on flood events, including detailed data about the effects of different flood characteristics on different building constructions and materials, and itemised costs of necessary repair/replacement works. It has proved difficult to gain this level of detail during the research into the development of the tool, partly due to issues of confidentiality, to lack of detailed records of past events, and division of responsibilities during and after the event.

Before calculating flood damage to a building, it is recommended to check its structural stability either by calculation (Nadal *et al.*, 2010) or by depth/collapse curves (e.g. USACE, 1985).

The range of different constructions and materials represented in the prototype IBT tool is still limited compared with what is available and used in buildings throughout Europe. To increase the tool's applicability as widely as possible, a larger choice of constructions should be offered in enhanced tool databases. This requires a major exercise of cataloguing and assessing typical construction methods and materials in the various countries, and this task is suggested for future development of the tool.

6. Conclusions

Simple methodologies and tools have been recently developed to assist in the flood risk management of urban areas, focusing particularly on buildings that can be considered critical for the normal functioning of urban areas. Unlike domestic construction, owing to their specificity, these buildings cannot easily be categorised in terms of type of construction or age, and have to be treated as individual buildings. This paper has summarised novel approaches and advances in this area, developed through recent European-funded projects such as FloodProBE.

It is expected that building owners, insurance companies, local authorities and agencies with urban flood-management responsibilities will benefit from the application of the frameworks and tools presented.

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