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ASSESSING THE EFFECTS OF FLOOD RESILIENT TECHNOLOGIES

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ABSTRACT

The impacts of floods on housing in urban areas are increasing due to both the intensification of extreme weather events and the development of settlements together with the rising vulnerability of assets in areas at risk. Therefore, the improvement of buildings' resilience properties to better cope with flooding is becoming a key issue in European research in recent years.

The implementation of flood resilience technologies (FRe T) on a building scale provides a previously untapped potential to reduce flood damage because of insufficient transparency of their effects. To overcome this obstacle the paper covers an extended methodological framework for the analysis of the potential of FRe T. This framework is based on a synthetic approach on flood damage simulation that supports the assessment of singular FRe T or the combination of several FRe T options and permits the derivation of optimised FRe T alternatives.

The approach has been tested, amongst other selected European study sites, in Heywood/Greater Manchester (United Kingdom) to analyse its functionality considering various flood types as well as different national and local contexts.

KEYWORDS
flood damage to buildings, flood resilience technologies, vulnerability mitigation.

1. INTRODUCTION

It is evident that flood impacts on housing in urban areas are increasing due to both the intensification of extreme weather events and the development of settlements together with the rising vulnerability of assets in areas at risk (White 2010).

Flood impacts on buildings are often extensive and can be described by the degree of experienced harm of its materials and structures and the deterioration of its physical functions (Blanco & Schanze 2012). A number of publications and studies have already described the damaging effects of flood actions on the building fabric (e.g. USACE 1998, Kelman 2002, Roos 2003, Kelman & Spence 2004, Naumann et al. 2009).

To mitigate flood impacts and to better cope with flooding the improvement of buildings' flood resilience is becoming an important strategy in flood risk management and a key issue in European research in recent years.

Flood resilience of buildings can be defined as their ability to recover easily and quickly from damaging effects (e.g. Lawson 2011). The enhancement of buildings' flood resilience properties is generally aiming at (i) minimising flood damage, (ii) decreasing direct flood repair costs, and (iii) allowing fast re-occupation. In this context flood resilience is inversely related to flood vulnerability.

However, the implementation of flood resilience technologies (FRe T) on a building scale provides a previously widely underestimated potential to reduce flood damage due to an insufficient transparency of performance.

Although various approaches are available for the assessment of flood damage to buildings (e.g. Scawthorn et al. 2006, Neubert et al. 2008), up to present these methods do not consider either the performance or the effects of different FRe T concerning damage mitigation.

Basically, flood resilient technologies (FRe T) are specified as any methods, products or materials that improve the resilience properties of the built environment (Lawson 2011). The research report of Kelly et al. (2011) identifies a broad variety of FRe T and assigns them to four predefined categories:

- Perimeter technologies
- Infrastructure technologies
- Building aperture technologies
- Building technologies

On urban scale particularly perimeter technologies such as mobile flood barrier systems, which are installed at some distance from groups of buildings, provide flood protection to specific locations up to a certain threshold. Infrastructure technologies provide protection to roads, railways etc. using surfacing materials, membranes or automatic barriers to maintain their functions. It should be noted that both FRe T categories are outside the scope of this paper, as it pays emphasis to the effects of FRe T at the property level.

On an individual building scale the set of FRe T comprises, first, building aperture technologies for the temporary watertight closure of façade openings such as doors, windows or ventilation elements and, second, building technologies that address either resilient building components or resilient engineering solutions for potentially flood affected building assemblies.

In general, the implementation of both building aperture technologies as well as resilient building components intends to keep flood water out of the building up to a defined design level. It is obvious that this dry proofing strategy is limited by the individual strength of the particular external wall constructions to withstand flood actions e.g. hydrostatic pressure without structural failure.

Resilient building components include materials for the temporary or permanent sealing of the building envelope, anti-corrosive products that prevent triggering destructive processes or smart domestic flood warning systems that operate automatically flood barriers.

In contrast, resilient engineering solutions are related to the wet proofing strategy. Although building aperture technologies and resilient building components are available in the market that can help avoid floodwater entering a building, there can nevertheless be a significant risk that building assemblies in flood-prone areas have to cope with floodwater, e.g. due to overtopping or failure. Hence, resilient engineering solutions provide advice on how to design new or how to modify existing building assemblies, e.g. external wall or floor constructions, in order to enhance cleanability, to promote fast drying and to minimise the extent of necessary repair works in case of flood water is entering the building. The recommendation of resilient engineering solutions considers material interactions in composite building constructions as well as their structural integrity and inherent resilient characteristics. Laboratory tests to determine the resilience properties of building assemblies have also been conducted e.g. by Escarameia et al. (2006), Gamerith & Hoefler (2006), Bowker et al. (2007), Escarameia et al. (2007), Gabalda et al. (2012), and Garvin et al. (2012).

A key criterion for the implementation of flood resilience technologies is having sufficient evidence about their level of performance. Therefore, within the EU-FP7-research project “Smart Resilience Technology, Systems and Tools“ (SMARTeST) a set of innovative and smart flood resilience technologies has been identified and tested by experimental studies.

Following Samuels & Gouldby (2010) performance is defined as the degree to which a process or activity succeeds when evaluated against some stated aim or objective. Performance indicators for FRe T are their reliability and efficiency.

Reliability is understood as the capability of FRe T to perform trustworthy their required functions under stated conditions. Based on harmonised test methods, consistent reliability studies were conducted for selected FRe T within the SMARTeST research project in order e.g. to analyse their capacity to withstand hydrostatic and hydrodynamic flood actions (failure) or to determine their intrinsic parameters such as the leakage rate (Gabalda et al. 2012).

Efficiency generally relates the positive effects (benefits) to the expenditures (costs) of FRe T implementation in monetary terms. The resulting benefit-cost ratio is an indicator that serves as a basis for the selection of most efficient FRe T alternatives to improve flood resilience. However, there is currently a significant uncertainty of FRe T efficiency due to a lack of scientific data of their positive effects (benefits).

To overcome this obstacle the paper covers an extended methodological framework for the analysis of the potential of FRe T. This framework is based on a synthetic approach on flood damage simulation that has already been comprehensively described in Neubert et al. (2013). The proposed framework supports the assessment of singular FRe T or the combination of several FRe T options and permits the derivation of optimised FRe T alternatives.

The approach has been tested, amongst other selected European study sites, in Heywood/Greater Manchester (United Kingdom) to analyse its functionality considering various flood types as well as different national and local contexts. The case study approach is used to demonstrate and to compare the effects of different FRe T implementation alternatives at a high spatial and contextual resolution.

2. METHODOLOGY

A methodology for analysing the flood vulnerability of properties that uses a synthetically approach for the determination of flood damage to buildings has already been described in Neubert et al. (2008), Naumann et al. (2009), Schinke et al. (2012), and Neubert et al. (2013). Based on the specific physical flood vulnerability the costs for repairing flood damage to buildings are calculated and visualised employing depth-damage curves. That methodology has now been extended to consider the effects of FRe T implementation.

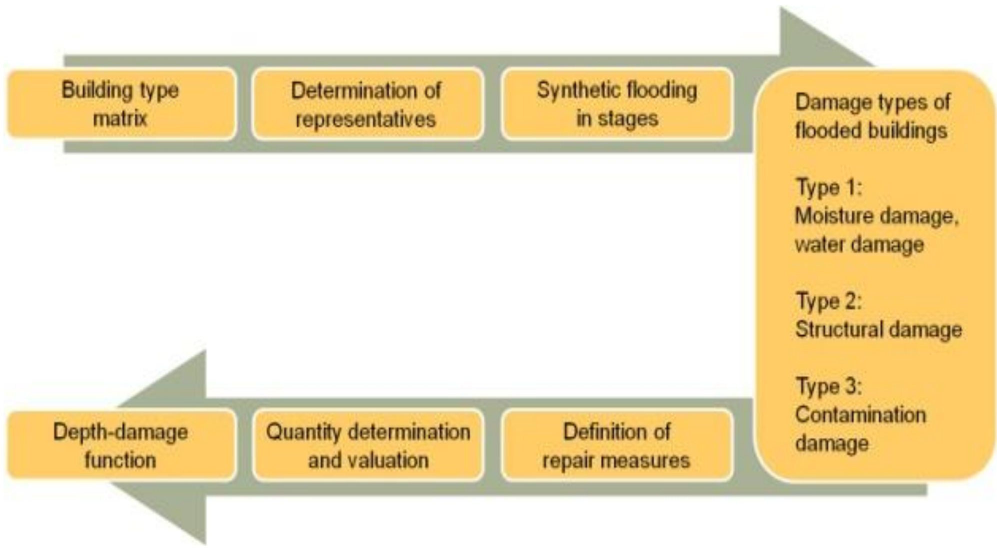

Figure 1: Methodological steps for the synthetic calculation of flood damage to buildings. Source: IOER 2008.

Generally, the development and application of depth-damage curves aggregated in different ways to calculate flood damage to buildings has already been established worldwide (Penning-Rowsell & Chatterton 1977, Veerbeek & Zevenbergen 2009, Naumann et al. 2009, Middelmann-Fernandes 2010).

The approach for the synthetic calculation of flood damage to buildings according to Neubert et al. (2013) requires seven processing steps (Fig. 1) for the synthetic calculation of flood damage.

The first processing step comprises the identification of settlement structures in the floodplain using a Geographical Information System (GIS) and remote sensing data. This step enables a level 1 classification of the entire building stock into pre-defined urban structure types (USTs). USTs are areas with physiognomic homogeneous characters of built-up areas marked by specific formations of buildings and open spaces. Building age groups are used at level 2 for a further subdivision of the building stock, as building age groups consider interrelations between the period of construction and the structural design of buildings. Then, building types can be derived by linking the attributes from structure type and building age group. As a result, an area-specific building typology differentiates and documents the stock in a targeted fashion with a focus on residential buildings.

In the second processing step, characteristic representative buildings are selected for each relevant building type and analysed concerning details of geometry, structural design, building fabric, technical infrastructure, and typical uses.

It is followed by the third processing step, which concerns the definition of specific inundation levels for the virtual flooding of selected building representatives.

In the forth processing step, physical damage processes for different inundation levels are analysed considering three characteristic damage types: moisture and water damage, structural damage, or damage due to contamination.

The definition of inundation levels in the fifth processing step helps to differentiate specific service ranges for repairing the indicated flood damage. Every inundation level comprises specific constructional elements that require certain measures for refurbishment.

Then, the costs of repairing flood damage are calculated in the sixth processing step. The cost estimates are following relevant professional literature on refurbishment planning.

In the seventh processing step, building-type-specific and synthetic depth-damage functions are derived to obtain a major result of the vulnerability analysis. Either quality-assured damage appraisals or detailed cost determinations of long-term and technically correct repairs after a flood event are necessary to validate the synthetic depth-damage functions.

To consider the potential to implement FRe T on a building scale the presented synthetic approach on vulnerability analysis was further developed and extended. Depending on the considered type of FRe T adapted depth-damage functions are established based on modified cost estimations due to a changed range of flood repair requirements.

The extended methodology has been implemented in the flood damage simulation model HOWAD-Prevent. This model calculates flood damage to buildings referred to certain water depths and considers the effects of FRe T employing adapted depth-damage functions.

3. RESULTS

The flood damage simulation model HOWAD-Prevent was applied in the Heywood/Greater Manchester (United Kingdom) to analyse flood damage to residential buildings for selected scenarios. These scenarios include, first, different heavy rain events resulting in diverse flood water depths in certain township areas and, second, different levels of FRe technology implementation resulting in a dissimilar extent of flood damage. Based on these analyses, the effects of FRe technology implementation concerning damage reduction were verified to support decision-making processes in the local flood resilient planning. It should be indicated that the individual performance level of FRe T is not covered in this study so far. It will be initially considered within further damage analyses.

Heywood is a town located in North West England within the Metropolitan Borough of Rochdale in Greater Manchester at an elevation of around 130 m above mean sea level. It lies about 11.9 km north of the city of Manchester and has a population of around 28,000. Heywood has been developed on the south bank of the River Roch and is flanked by the Pennine hills in the north and east. The study area is drained by two partly covered streams Wrigley Brook and Miller’s Brook flowing into the River Roch. The main urban area is a high-density residential and industrial site, originally developed between 1750 and 1900. Since 1960 many open areas and brown field sites, both within the town and on it southern margins have been occupied by new housing and new low-rise, large warehouses on a new distribution centre.

Prior 2004, Heywood, Rochdale, Greater Manchester had almost no history of flooding. The area was experienced only by minor, highly localised flooding in the past. There is solely some evidence of regular, annual flooding of road surfaces in one small housing estate. However, in 2004 and 2006 short duration, high intensity, summer thunderstorms induced serious pluvial flooding at six distinct locations within the township. The 2006 event resulted in over 200 homes being inundated with up to 900 mm of sewage contaminated water for up to 3 hours and around 90 properties had to be evacuated for varying time-spans whilst renovation was taking place.

All six areas, which experienced substantial flooding, are located along two urban streams that have been previously culverted. Some reaches of these streams are up to present date part of an inadequate combined sewer system that is used to drain surface runoff as well as wastewater. Besides the heavy precipitation, restricted sewer capacity was responsible for flooding on both occasions in 2004 and 2006. Pluvial flooding in Heywood is caused by sewer overflow due to hydraulic overload. It should be noted that none of the affected residential buildings was charted on the Environment Agency’s floodplain map, because of the high uncertainty in quantifying pluvial flood risks. The climate change induced increased severity and frequency of storm events presumably make the area highly vulnerable to pluvial flash floods in future.

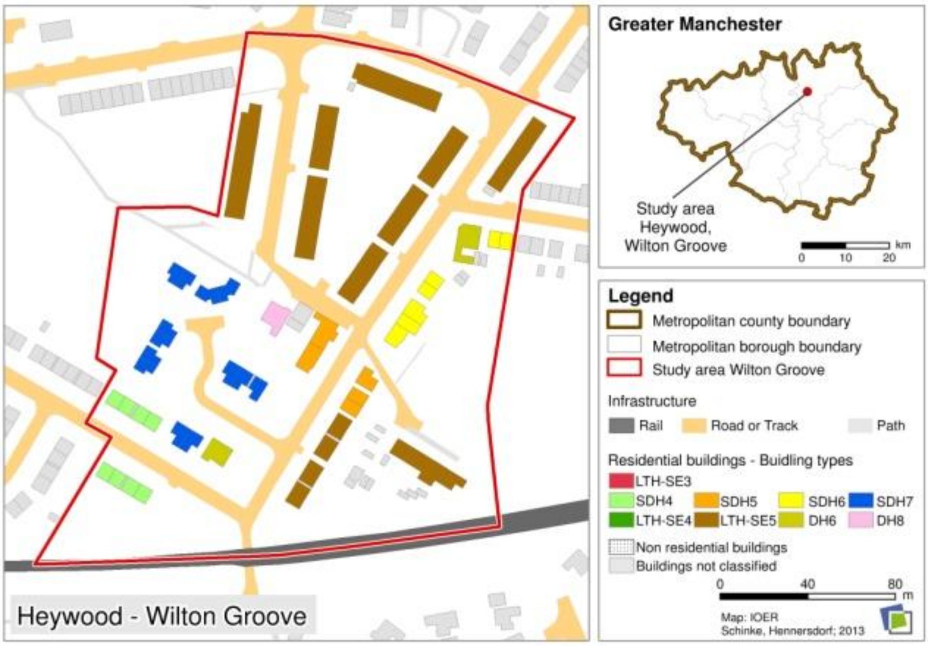

Figure 2: Classified building types for the study area Wilton Grove in Heywood.
Source: IOER 2012.

One of the six potentially affected urban areas is Wilton Grove, a small catchment in the south of Heywood that is used to demonstrate exemplarily the effects of FRe T implementation (Fig. 2). The area Wilton Grove is dominated by two building types (Fig. 3) that were classified during engineering field surveys:

- Terraced houses that have been constructed in the post war period between 1945 and 1965 (LTH-SE 5)
- Semi detached houses that have been constructed between 1980 and 1995 (SDH 7)

Other existing, but minor relevant building types are e.g. terraced houses constructed in the interwar period (LTH-SE 4) as well as semi detached houses erected either between 1945 and 1965 (SDH 5) or between 1965 and 1980 (SDH 6).

Figure 3: Most relevant residential building types in the study area Wilton Grove. Left: Terraced house between 1945 and 1965 (LTH-SE 5). Right: Semi detached house between 1980 and 1995 (SDH 7). Source: IOER 2012.

It was intended to analyse the effects of FRe T implementation on building scale in the area Wilton Grove. Therefore, a series of simulations were undertaken covering (a) building aperture technologies and resilient building components to prevent water ingress (dry proofing strategy) and (b) resilient engineering solutions (wet proofing strategy) that limit flood damage in case water is entering the building.

Table 1: Selected FRe T for the building type LTH-SE 5 to test their potential to enhance buildings' resilience properties.

selected FRe T to follow the dry proofing strategy	*selected FRe T to follow the wet proofing strategy*
temporary flood guards (boards) for doors	modified ground floor construction using e.g. foam glass and mastic asphalt screed
air-brick covers	modified external wall: construction using e.g. polyurethane cavity wall insulation
valves for backflow prevention	

Particularly the draft of flood resilient engineering solutions for the detected building types requires imperatively in-depth knowledge about their typical building fabric that was used commonly during their construction period, as it has a significant impact on their flood susceptibility (Naumann et al. 2009). That technical expertise was explored by professional literature review and engineering field surveys and serves as a basis for the derivation of profound recommendations for the design of resilient building assemblies. Resilient engineering solutions are often individual for each building type due to their specific constructive requirements and are therefore not readily transferable.

To validate the extended methodology FRe T were implemented at each relevant building type in the study area. Table 1 shows exemplarily selected FRe T options for the building type LTH-SE 5 that have been tested regarding their potential to enhance resilience.

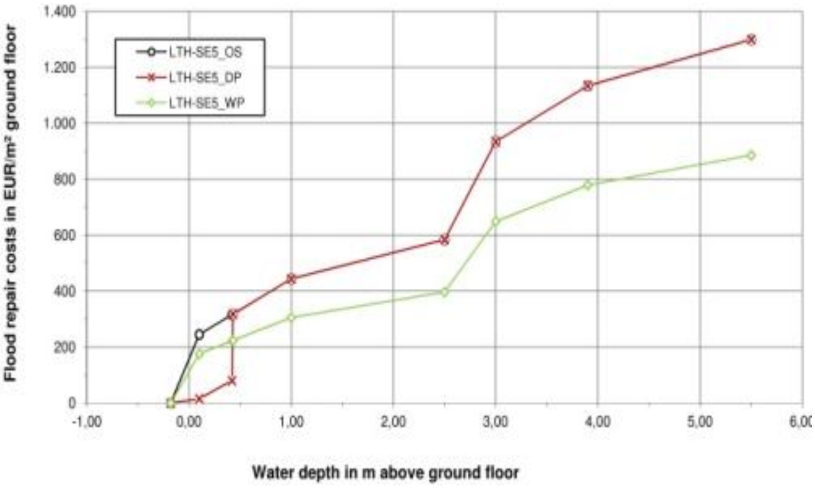

Figure 4: Exemplary depth-damage functions (DDF) for the building type LTH-SE 5. The three displayed DDF are indicating building types' flood vulnerability. The reference value is the water depth above ground floor:
Black function: for the original state considering no FRe T implementation
Red function: for the dry proofed state considering building aperture technologies and resilient building components
Green function: for the wet proofed state considering flood resilient engineering solutions
Source: IOER 2012.

Detailed depth-damage functions for building types based on individual damage processes were adopted to allow calculating the potential of FRe T implementation regarding flood damage reduction. Figure 4 provides exemplarily three depth-damage functions for the building type LTH-SE 5. It is apparent that the costs of flood repair can be substantially reduced by FRe T implementation. Particularly below the design level of building aperture technologies and resilient building components, which prevent water ingress (dry proofing strategy), the potential flood damage to the building structure can be reduced (red-coloured function in Fig. 4). If the intake threshold is exceeded, these FRe T are ineffective. Resilient engineering solutions (wet proofing strategy) are characterized by the function's diminished slope (green-coloured function in Fig. 4).

ENPC (2012) has simulated geo-referenced flood water levels for certain precipitation scenarios within "Wilton Grove". One selected precipitation scenario covers an event of 58.5 mm of rainfall in 2 hours. This scenario simulates a severe rainfall event that took place in that area at August 3rd 2004. Modelling results provide water depths in the study area vary between 5 cm and 65 cm.

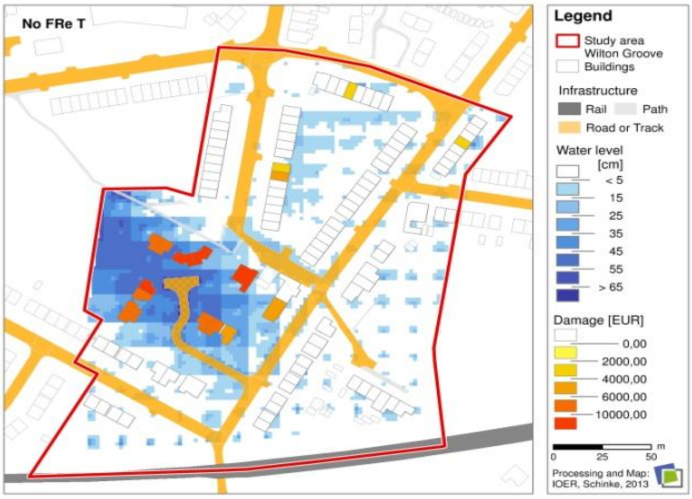

Figure 5: Flood damage to buildings in monetary terms for the reference scenario without FRe T implementation.
Source: IOER 2012, ENPC 2012.

Flood damage to buildings in Wilton Grove is calculated for each scenario using the HOWAD-Prevent tool. A reference scenario covers the case that no FRe T are implemented and provides a benchmark for comparison (Fig. 4). The four other scenarios cover two levels of FRe T implementation on building scale separated for the dry proofing and the wet proofing strategy (Fig. 5):

- 30% = realistic value of FRe T implementation, i.e. it is assumed that 30% of all buildings in the study area use FRe T for flood damage mitigation
- 100% = optimistic value that indicates the full FRe T implementation potential

Assuming a realistic value of FRe T implementation in Wilton Grove, the calculation is based on Monte Carlo methods that rely on repeated random simulations to obtain numerical results for the flood damage to buildings.

Figure 6 provides four damage maps for the heavy rain event of 58 mm / 2 hours. It became evident that the implementation of building aperture technologies and resilient building components (dry proofing strategy) are highly effective to reduce significantly flood damage to buildings (Fig. 6, No. 3 and 4), particularly for low flood depths up to 40 cm. The direct costs for repairing flood damage to buildings in the study area can be reduced approximately by 25% (Fig. 6, No. 3 realistic implementation level) or up to 80% (Fig. 6, No. 4 optimistic implementation level). However, to take advantage of the high potential of dry proofing, it is needed to achieve a high level of implementation, so that their applicability in case of flooding is guaranteed.

Generally, resilient engineering solutions (wet proofing strategy) are effective at any time regardless of any flood warning time, personal efforts, potential operating errors, and leakage rates. However, in case of Wilton Grove they are less effective than building aperture technologies due to the potentially expected flood water depths. The direct costs for repairing flood damage to buildings can be reduced approximately by 15% (Fig. 6, No. 1 realistic implementation level) or up to 50% (Fig. 6, No. 2 optimistic implementation level). Though, higher water levels would increase significantly the potential of resilient engineering solutions to reduce flood damage to buildings.

It should be noted that one building in the centre of the map remains with relatively high flood damage (red coloured). This building is assigned to the building type DH 8. The implementation of any building-related FRe T is not feasible due to its timber frame construction.

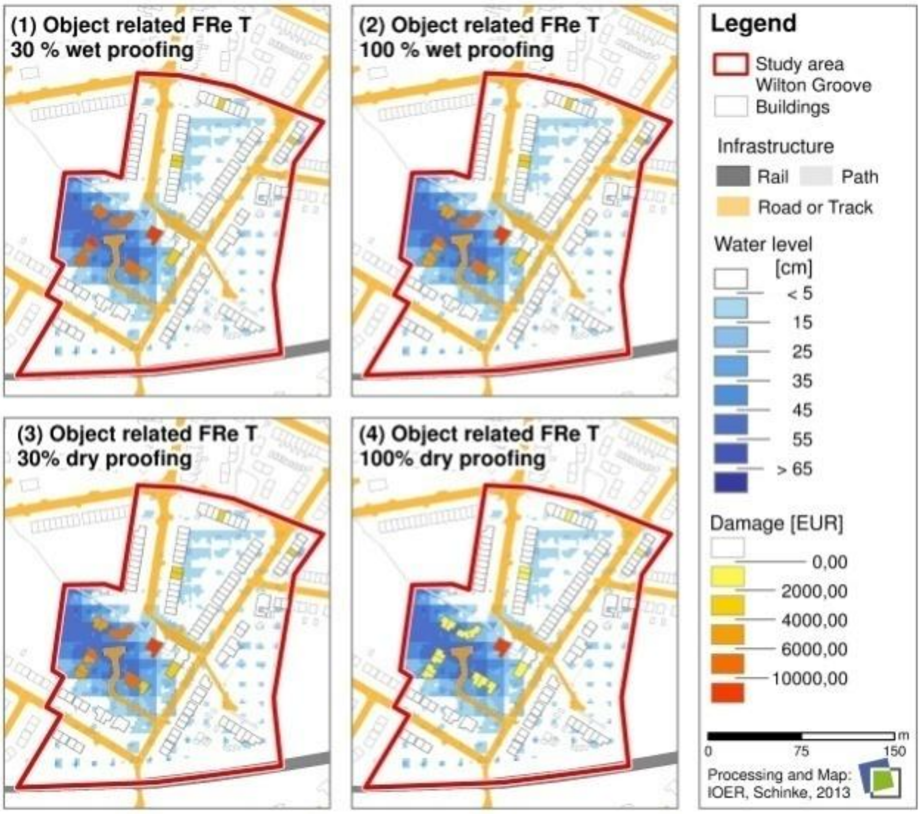

Figure 6: Flood damage to buildings in monetary terms for a heavy rain event of 58 mm / 2 hours considering different FRe T implementation levels.
Left: Damage maps for the scenarios 1 and 3 that cover the case that 30% of all buildings in the study area use either flood resilient engineering solutions for wet proofing (top) or building aperture technologies and resilient building components for dry proofing (bottom).
Right: Damage maps for the scenarios 2 and 4 that cover the case that 100% of all buildings in the study area use either flood resilient engineering solutions for wet proofing (top) or building aperture technologies and resilient building components for dry proofing (bottom)
Source: IOER 2012, ENPC 2012.

4. DISCUSSION AND CONCLUSIONS

The proposed methodology, which has been initially tested in three case study areas in Heywood (United Kingdom), Valencia (Spain) and Dresden (Germany), has the potential to assess the effects of FRe T within flood damage calculations.

However, further work will be done to consider also the expenditures (costs) of FRe T in monetary terms in order to calculate the efficiency of their implementation. Basically, efficiency is relating the effects (benefits) to the costs and can be expressed by the formula:

$$Efficiency = Effects/Costs$$

In addition, detailed information about the reliability of various FRe T resulting from laboratory testing or numerical modelling will be gathered in order to link the parameters reliability and efficiency to obtain an indication of their performance. The SMARTeST research report (Gabalda et al. 2012) provides a general evaluation scheme of FRe T reliability that has already been used for the reliability assessment of about 25 tested FRe T. These test results will be analysed to identify trustworthy working FRe T. Then, the parameter performance can be determined by the expression:

$$Performance = Reliability * Efficiency$$

It will serve as profound basis for the selection of most appropriate FRe T alternatives. Finally, the methodology of flood damage assessment will be improved to capture prospective FRe T performance.

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