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OVERVIEW

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Implementation of property-level flood risk adaptation (PLFRA) measures: Choices and decisions

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Abstract

Hydrometeorological events are highly costly and have strong impacts on the human-environment system. Effective response requires effective risk management concepts and strategies at individual and watershed level to increase community resilience. Focusing on flood risk and the information associated with it, individual risk behavior in the shape of implementing property-level flood risk adaptation (PLFRA) measures is often overlooked. For this research, a comprehensive overview of possible PLFRA measures for homeowners in flood risk areas was made, as well as the possible costs and technical feasibility for new and existing buildings. To complement this, insights into risk mitigation behavior are essential due to the ongoing shift to risk-based and individualized flood risk management, which require a contribution from flood-prone households to risk reduction. Results show that PLFRA measures differentiate in their effectiveness, cost-efficiency and technical feasibility, and full protection can never be guaranteed. Considering risk mitigation behavior, literature generally distinguishes between situational factors (such as communication and economic subsidies) and personal factors (such as personal and psychological components influencing individual behavior).

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KEYWORDS

adaptation, adaptive capacity, flood risk management, property-level flood risk adaptation measures, resilience, risk behavior

1 | INTRODUCTION

Recent developments show an increasing risk of extreme hydrometeorological events owing to land-use change, climate change, loss of flood storage capacities alongside rivers, and alterations to agricultural practice and land-use management (Blöschl et al., 2015, 2017; Fuchs et al., 2017). Despite considerable efforts to reduce flood risk through technical solutions, losses have remained significant across the world just as in past decades (Klein et al., 2019; Mechler & Bouwer, 2015). Impacts result from the frequency and magnitude of flood hazard events and increasing exposure of buildings and infrastructure, but also from the level of vulnerability of residents and businesses (Fuchs et al., 2019; Mechler & Bouwer, 2015; Papathoma-Köhle, Gems, Sturm, & Fuchs, 2017; Penning-Rowsell et al., 2013; Sturm et al., 2018a, 2018b). Consequently, current policy strategies, documents and legal frameworks revolve around making citizens and economies more resilient against future events (Fuchs & Thaler, 2018; Laeni, van den Brink, & Arts, 2019; Meng, Dabrowski, Tai, Stead, & Chan, 2019; Spaans & Waterhout, 2017). Within integrated flood risk management the implementation of structural flood alleviation schemes (e.g., dikes) and nonstructural solutions (e.g., land use policy, early warning, property-level flood risk adaptation [PLFRA] measures) is emphasized (Green, 2017; Holub, Suda, & Fuchs, 2012; Joseph, Proverbs, & Lamond, 2015; Kreibich et al., 2017).

Implementing PLFRA measures focuses mainly on the individual household level because technical protection schemes, such as dikes, are often understood as public flood risk management strategies. Some of the main subjects to justify individuals to take personal responsibility in flood risk management include: (a) hydrological or geomorphological justification as river beds in some communities confine the implementation of public flood alleviation schemes due to limitations of space; (b) engineering justifications, especially referring to residual risk (failure of dikes); (c) grassroots organizations, especially if citizens disagree with public flood alleviation schemes in their neighborhoods (so called "Not in my Backyard effect"); (d) legislative-economic justification, such as low or negative benefit-costs ratio; and (e) political statements, where flood risk management is seen to be a private good rather than a public good. Therefore, policy documents and recent academic research center on individual homeowners to address the flood hazard problem (Burns & Slovic, 2012; Kerstholt, Duijnhoven, & Paton, 2017). Nevertheless, the critical question is: what drives/motivates private people to adapt to flood hazards? There are various trigger mechanisms that might (or not) encourage individual risk behavior (Bamberg, Masson, Brewitt, & Nemetschek, 2017; Van Valkengoed & Steg, 2019; Werg, Grothmann, & Schmidt, 2013).

This paper focuses on reviewing which measures might be suitable to implement as a means to increase the preparedness in private households, but also how situational and personal factors might (or might not) influence individual behavior to successfully implement PLFRA measures. The link between behavioral studies and engineering solutions should be connected more strongly, as whether a PLFRA measure is implemented and which type is chosen, largely depends on situational and personal factors. One can distinguish mechanisms between situational factors (also known as external trigger mechanisms), which assess the impact of risk communication, insurance payments and subsidies to individual risk behavior, and personal factors, including personal and psychological components such as place attachment, trust in government and implemented measures, self-efficacy, or risk perception and experiences.

2 | CATALOGUE OF PLFRA MEASURES

PLFRA has its emphasis on the physical resilience of buildings (Aerts & Botzen, 2011; Aerts, Botzen, De Moel, & Bowman, 2013; Kreibich, Bubeck, Van Vliet, & De Moel, 2015; Kreibich et al. 2011a), which includes but is not limited to design and static resistance in order to meet building codes and other measures targeted at reducing the physical impact of hazards on the building envelope. These strategies can diminish the impact of flood events and are in some cases cost-efficient (Holub & Fuchs, 2008), but largely differ in costs and effectiveness. Implementing PLFRA measures therefore demands self-responsibility, as these measures are usually voluntary (Kreibich et al., 2015). This paper discusses five main strategies to protect properties at risk (Tables 1–6): (a) avoidance of flood discharge (stay clear of flood waters), (b) wet flood-proofing (accepting flood waters), (c) dry flood-proofing (rejecting flood waters), (d) barriers, and (e) other mitigation measures. In the following sections, the measures will be discussed in further detail. A distinction whether measures are technically feasible in new and existing buildings is made and approximate costs of several different geographical regions are compared. All measures presented in this paper can be implemented on detached houses (residential single-family homes) and in some cases also on apartment buildings. However, it has to be considered, that the efficiency of each PLFRA measure is highly dependent on the flood probability, the construction design of the individual property at risk and the type of flood present. Also, local construction traditions influence the possibility of implementing certain PLFRA measures. Concerning the velocity of floods, in areas of high velocity flooding hydrodynamic and debris actions might dominate, whereas in areas of groundwater flooding hydrostatic and buoyancy actions might be more important. Thus, the design of PLFRA measures always depends on given flood dynamics (Proverbs & Lamond, 2017). Full protection is financially and technically not possible as there will always be existing residual risk. Also, the implementation of some measures will require expert support.

2.1 | Avoidance of flood discharge

This section includes PLFRA measures, which have the goal to avoid flood discharges, by either adapting the surrounding area of the building at risk, or the building itself (Table 1).

TABLE 1 Possible flood avoidance measures, the approximate costs (€), whether they are temporary or permanent when installed and their technical feasibility in new or existing buildings (+ technically feasible, ± technically partly feasible, − technically not feasible; n/a = information not available)

			Technical feasibility		Approximate cost		
Measures	**Measures: Detail**	**Temporary/ Permanent**	**New building**	**Existing building**	**New building**	**Existing building**	**Source of approximate costs**
Landscape design		Permanent	+	+	n/a	n/a	
Flood plains		Permanent	+	±	n/a	n/a	
Drainage for surficial water		Permanent	+	+	n/a	n/a	
Design and shape of building		Permanent	+	−	n/a	n/a	
Elevating building	Elevating 60–180 cm	Permanent	+	±	€2,000–€7,000 (per house)	€29,000–€32,000 (per house)	(Aerts et al., 2013)
	Elevate column 50–100 cm	Permanent	+	n/a	€1,200–€2,000 (per house)	n/a	(Gersonius, Zevenbergen, Puyan, & Billah, 2008)
	Elevate wall 30–90 cm	Permanent	+	n/a	€2,000–€4,300 (per house)	n/a	(Gersonius et al. 2008)
Raising the ground floor level		Permanent	+	n/a	€27,000–€50,000 (per house)	n/a	(Kreibich et al., 2015)
Buildings on partially elevated areas		Permanent	+	−	n/a	n/a	
Floating/ amphibious buildings		Permanent	+	−	10% higher than land-based houses	n/a	(Witsen, 2012)

- *Landscape design*: Effective site drainage and managing surface water runoff can reduce the flood risk of a property by adapting the area surrounding the building at risk (CIRIA, 2007). This can include the process of greening surrounding surfaces in order to increase the subsurface drainage (Zevenbergen et al., 2011). Changes in the landscape design are generally permanent and cost effective for the entire community. Nevertheless, when the landscape design is changed, it is vital to consider adjacent buildings in order not to increase their flood risk (Bowker, 2007). This type of adaptation is possible both for new and existing properties (Holub & Hübl, 2008).
- *Building on elevated ground*: Another measure used to avoid floodwaters is building on elevated ground. This can successfully be done during the development process of newly constructed buildings. Hereby, the landscape design has to be taken into consideration during the planning process of new developments (Egli, 2005).
- *Elevation*: Elevating, by raising a building above the flood level, is a permanent and effective method to reduce flood risk (Figure 1). It can be achieved if either the entire home is elevated or there is a newly raised floor within the house. In the United States, a government-promoted retrofitting strategy in flood-prone areas is permanent static elevation (FEMA, 2014). If raising a building retrospectively, it firstly has to be separated from its foundation. Thereafter, a new foundation or extension of the foundation is constructed which can consist of piers, posts, columns, continuous walls, or piles (Aerts et al., 2013). Elevating masonry is costlier than frame constructions with a basement or crawlspace (Aerts et al., 2013). Additionally, stone buildings are costlier than wooden buildings. Considering the costs of elevating buildings seen in Table 1, it becomes apparent that it is less costly if done during the construction process, than retrospectively (Kreibich et al., 2015) and is thus more common and suitable for new buildings. Elevation is especially common in areas which are prone to seasonal flooding, such as the Mekong Delta in Vietnam (Liao, Le, & Nguyen, 2016) or the Tonlé Sap lake in

Cambodia (Nuorteva, Keskinen, & Varis, 2010). In the United States and Australia, where wood framed constructions are more common, houses are largely raised on pillars (Proverbs & Lamond, 2017). Elevated houses and specifically the piers, columns, and so on must be able to withstand the hydrostatic pressure caused by the flood water and possible impacts by debris and erosion (FEMA, 2014). Additionally, it has to be considered, that elevated houses are more prone to wind damage, especially along coastal regions (English, Friedland, Orooji, & Mahtani, 2015).

- *Amphibious buildings*: Amphibious buildings are an alternative to permanently elevating structures, as they rise with flood waters (English et al., 2015). There is a long history of such buildings and various examples can be found worldwide depending on the climatic conditions, the culture and construction materials available (Strangfeld & Stopp, 2014). Materials such as hollow concrete pontoons or polystyrene blocks are used as a foundation to create buoyancy (Zevenbergen et al., 2011). Guidance posts prevent the house from floating away, making only vertical movements possible (English et al., 2015). In many cases, buildings are also rested upon poles or concrete slab foundations (Zevenbergen et al., 2011). Compared to elevated buildings, amphibious buildings are not as exposed to high wind velocities and can withstand larger flood events. Examples include the floating village IJburg Waterbuurt in Amsterdam and Maasbommel at the Maas River, both in the Netherlands (Witsen, 2012), which are newly planned quarters. Considering costs of floating buildings as seen in Table 1, it becomes apparent that it is a rather exclusive product in Europe and is not yet a very common retrofitting measure.

2.2 | Wet flood-proofing

So called wet flood-proofing measures are a combination of measures which allow flood waters to enter and exit a building in order to keep constant pressure on the exterior and interior of the structure (Table 2). This decreases the chance of wall failures and structural damage (FEMA, 2014). Wet flood-proofing measures are in most cases less costly than other measures and less space for construction is required. Nevertheless, wet flood-proofing measures require clean up, and sewage and chemicals make homes uninhabitable for some time after the event. Additionally, the measures have to be maintained periodically and cannot minimize the damage related to potential large flood events (FEMA, 2007), as the capacity of damage reduction decreases remarkably if flood water levels exceed 2 m (Poussin, Bubeck, Aerts, & Ward, 2012). According to Kreibich et al. (2015), wet flood-proofing can reduce damage effects by as much as 46% (flood adapted use), 53% (flood adapted interior fitting) and 36% (installation of heating and electrical utilities in higher elevation than the flood level).

As wet flood-proofing allows floodwaters to enter a building, objects have to be made of water resistant materials. Therefore, such measures are most appropriate for basements or other nonliving areas (FEMA, 2014). Wet flood-proofing is no longer effective if inundation depths are larger than 3 m (Lasage et al., 2014). If objects in these areas cannot be moved to a higher floor, they can be protected by enclosing structures made of waterproof materials, such as concrete (FEMA, 2007).

TABLE 2 Possible wet flood-proofing measures, the approximate costs (€), the implementation type and their technical feasibility (+ technically feasible, ± technically partly feasible, − technically not feasible; n/a = information not available)

			Technical feasibility		Approximate cost		
Measures	**Measures detail**	**Temporary/ Permanent**	**New building**	**Existing building**	**New building**	**Existing building**	**Source of approximate costs**
Flood adapted interior	Moving kitchen to the first floor	Permanent	+	±	n/a	€6,000–€6,600 (per house)	(Kreibich et al., 2015)
	Move electrics above likely flood level	Permanent/ Temporary	+	±	€400 (per house)	€570 (per house)	(Kreibich et al., 2015)
	Situate important rooms in a higher level	Permanent	+	±	n/a	n/a	
Pump to remove water (sump pump)		Permanent	+	+	€1,500	n/a	(Aerts et al., 2013)
Floor drain standpipes (flood guard)		Permanent	+	+	€20	n/a	(CSI n.a.)

Sump pumps, for example, are installed at a low point in a building in order to be effective. This system has the goal to assist during a flood event. These pumps usually automatically start and thus require power supply. The water should not be pumped out of the building until the water level on the outside has decreased, since basement walls could collapse (FEMA, 2007). Sump pumps can be implemented as a retrofitting measure or during the construction process of a new building. On the other hand, flood adapted interior typically refers to moving valuables, electrics, sewage, and heating systems to higher levels. This measure is less costly and easy to apply during the construction process of new buildings, as the interior design can be planned appropriately (Kreibich, Thieken, Petrow, Müller, & Merz, 2005).

2.3 | Dry flood-proofing

Dry flood-proofing measures have the goal to prevent water from entering a building at risk (Table 3). In many cases, the measures do not protect buildings from high-magnitude dynamic flooding and are thus only effective for water depths of up to 1 m. Thereafter, the pressure of the water might become too large for the walls of the building (Lasage et al., 2014). Additionally, several measures have to be maintained periodically and do not eliminate the need to evacuate during a flood event, as residual risk is always present. Moreover, some types of retrofitting may require very invasive implementation (FEMA, 2014). According to Kreibich et al. (2015), dry flood-proofing a building can reduce damage by up to 60%. Dry flood-proofing measures are estimated to be 2.5 times more expensive than wet-proofing measures per house (Lasage et al., 2014).

Examples of such measures include:

- *Flood proof basement windows*: These are implemented to open outwards, as the pressure from the floodwater presses the window into its frame, additionally sealing it (Treberspurg et al., 2012). Some windows can be tilted and include an automatic closing system, whereas others have to be closed manually. An example of an automatically closing system, which responds to rising floodwaters can be seen in Figure 2. Such windows are installed for inundation depths of 1 to 1.8 m. The materials used for the frames are aluminum and galvanized steel as these are the most water resistant materials.
- *Sealed light shafts*: Many buildings have basement windows for ventilation and lighting purpose. Light shafts are needed and should be sealed from potential water inlet during flood events by using moveable steel covers with rubber sealants. These shafts can then be closed manually in case of a flood event. When protection is not needed, shafts can be left open for air ventilation and lighting. Alternatively, light shafts can also be sealed using glass bricks. Reinforced concrete has to be used in cases where floodwaters carry large amounts of sediments and bear erosion processes, as synthetic materials cannot withstand the impact of solid materials (Treberspurg et al., 2012).
- *Window and door guards*: This measure can be implemented on the exterior of a building and is implemented using waterproof steel frames which are fastened to the shutters. The windowsills are made using steel, timber, or stainless steel and provide effective protection against the impact of solids. Temporary elements are then used as a protection in case of a flood event (stop logs, aluminum boards, etc.) as seen in Figures 3 and 4 (Treberspurg et al., 2012).
- *Drainage*: During flood events, water levels in the sewage system may rise and lead to an overload in the system (BMNT, 2019). To prevent contaminated water to enter buildings, nonreturn valves can be implemented (Bowker, 2007).
- *Waterproof cellar using bitumen sealing (black tank)*: Buildings can be made waterproof from the outside by sealing basements using polymer bituminous seal, usually in new buildings. In the case of retrofitting, sealants are applied on the inside which is technically challenging and very costly (Manojlovic & Pasche, 2007). In practice, this type of sealing is often used, as basements can thus be used more effectively, compared to when sealing using waterproof concrete. The measure has an average lifetime of 75 years.
- *Waterproof cellar using waterproof concrete (white tank)*: Waterproof concrete can be applied to the inside area of basements. Since this measure is not completely waterproofing a building because of a possible seeping of moisture into the walls through capillarity and resulting water vapor diffusing inside the building, additional measures might be needed especially in areas with high groundwater levels (Suda & Rudolf-Miklau, 2012). Implementing waterproof concrete is only possible for new buildings (Egli, 2002). The measure has an average lifetime of 75 years (Kreibich et al. 2011b).
- *Building materials*: The resistance of materials to water inundation varies greatly. Using timber for walls, windows, windowsills, doors, and stairs results in only moderate resistance to water. An immediate problem of timber is that the material swells if unprotected. Timber will decay in the long term if the amount of moisture stays high over a longer period. Materials such as masonry and concrete are better options, even if bricks and concrete blocks can be saturated and leakage can occur through mortar joints. In the long-term, frost damage in winter and desiccation is possible (Zevenbergen et al., 2011). Table 4 shows suitable und unsuitable materials for construction in flood prone areas.

TABLE 3 Possible dry flood-proofing measures, the approximate costs (€), the implementation type and their technical feasibility (+ technically feasible, ± technically partly feasible, − technically not feasible; n/a = information not available), *personal communication with the manufacturers

Measures	Measures: Detail	Temporary/ Permanent	Technical feasibility: New building	Technical feasibility: Existing building	Approximate cost: New building	Approximate cost: Existing building	Source of approximate costs
Sealing building openings	Flood proof basement windows (100 × 100 cm) (wall thickness 24–30 cm)	Permanent	+	+	€450 (per window)	€450 (per window)	(Thermozarge LAGUN® 2019)*
	Flood proof basement windows (100 × 100 cm) (wall thickness 33–39.5 cm)	Permanent	+	+	€500 (per window)	€500 (per window)	(Thermozarge LAGUN® 2019)*
	Tiltable flood proof basement windows (100 × 100 cm) (wall thickness 20–30 cm)	Permanent	+	+	€893–€1,154 (per window)	€893–€1,154 (per window)	(Thermozarge LAGUN® 2019)*
	Tiltable flood proof basement windows (100 × 100 cm) (wall thickness 31–42 cm)	Permanent	+	+	968–€1,221 (per window)	€968–€1,221 (per window)	(Thermozarge LAGUN® 2019)*
	Sealed light shafts (100 × 50 cm)	Permanent	+	+	n/a	€ 800 per unit	(Hain System-Bauteile 2017)*
	Airbrick cover	Temporary	+	+	€200–€1,800 (per 12 airbrick covers)	€200–€1,800 (per 12 airbrick covers)	(Bowker, 2007)
	Door guards using stop logs (three stop logs in the size 200/50 mm including Installation)	Temporary	+	+	€1,690	€1,690	(Hochwasserschutz Reitthaler 2017)*
	Window guards	Temporary	+	+	€60–€90	€60–€90	(Ogunyoye, Stevens, & Underwood, 2011)
Elevated light shafts (100 × 50 cm)		Permanent	+	+	n/a	€650	
Check valves (nonreturn valves)	110-mm waste pipe	Permanent	+	+	€600–€70	n/a	(Ogunyoye et al., 2011)
Backup valves		Permanent	+	+	€2,700–€4,500	n/a	(JBA Consulting 2013)
Overhead sewers		Permanent	+	-	€950	n/a	(Aerts et al., 2013)
Toilet pan seals		Permanent	+	+	€60	€ 60	(CSI n.a.)
Waterproof cellar using bitumen sealing		Permanent	+	±	€465.10 per m^2	n/a	(Kreibich, Christenberger, & Schwarze, 2011b)
Waterproof cellar using waterproof concrete		Permanent	+	−	€505 per m^2	n/a	(Kreibich et al. 2011b)

TABLE 4 Construction materials and the suitability in flood prone areas based on Austrian national standards (ÖNORM) (Reprinted and translated with permission from BMNT (2019), p. 37. Copyright 2019, BMNT)

Use	Unsuitable building materials (not water-resistant)	Suitable building materials (water-resistant)
Exterior walls and cladding	Not water-resistant timber and wood panels	• Yellow foundation insulation board - expanded polystyrene foam (EPS-P, EPS-S), and extruded polystyrene foam (XPS-R) complying with ÖNORM B 6000 • Mineral plaster based on cement or hydraulic lime (ÖNORM EN 988-1, EN 459-1, B 3345) • Organically bound plasters (EN 15824) • Silicate plasters • Artificial resin plaster • Fiber cement board • Stainless steel sheets
Walls	• Gypsum plasterboard • Wooden walls, beams and planks • Aerated concrete, autoclaved aerated concrete • Steel girder	• Concrete, lightweight concrete • Conventional stone on stone construction (sand-lime brick, brick, etc.) • Glass bricks
Windows/ Doors	• Wood (unsealed, untreated)	• Wood (sealed, pretreated) • Synthetic materials • Aluminum
Interior walls and covering	• Gypsum plaster • Gypsum plasterboard • Wallpapers • Wood paneling • Cork cladding	• Mineral plasters based on cement or hydraulic limestone • Wall tiles • Clinker
Flooring	• Parquet • Wood plaster • Textile coverings • Linoleum • Cork	• Concrete • Screed • Tiling • Mastic asphalt
Thermal insulation	Fiber insulation materials (wood fiber, mineral wool, hemp, sheep wool, straw, cellulose, etc.)	• Foam glass • Yellow foundation insulation board EPS-P, EPS-S, and XPS-R complying with ÖNORM B 6000

2.4 | Barriers

Permanent and/or mobile barriers can stop the intrusion of water into individual structures or larger areas of land (BMNT, 2019). Barriers include stop logs, levees and berms, floodwalls and flood doors, as well as other semipermanent systems. However, barriers need to be maintained and local drainage systems might be affected to an extent that flood problems are worsened for adjacent buildings (FEMA, 2014). Numerous products exist (see Table 5).

- *Free standing barriers (Stop logs)*: Homeowners can protect objects at risk by installing permanent attachment measures and storing temporary stop logs (BMNT, 2019). Stop logs are usually made of aluminum and can protect large areas of several hundred square meters (Suda et al., 2012). The implementation process of stop logs often requires two people, as one stop log can weigh approximately 6–10 kg per meter (personal communication).
- *Floodwalls*: They are made of reinforced concrete and typically surround either an entire object at risk or smaller objects or openings (doors, windows, etc.). It can be integrated in the architecture of a building by using materials such as decorative blocks or bricks. Moreover, floodwalls are more resistant to erosion than structures made of compacted earth. Usually, this type of protection is used for areas where there is too little space for levees (FEMA, 2007).
- *External flood door*: External flood doors act as an alternative to temporary door protection measures and can be made of unplasticized polyvinyl chloride (uPVC), fiberglass, or metal with rubber gaskets (Bowker, 2007).

TABLE 5 Possible barrier systems, the approximate costs (€), the implementation type and their technical feasibility (+ technically feasible, ± technically partly feasible, − technically not feasible; n/a = information not available); *1 linear foot = 0.3048 m; ** personal communication with the manufacturers

Measures	Measures: Detail	Temporary/ Permanent	Technical feasibility: New building	Technical feasibility: Existing building	Approximate cost: New building	Approximate cost: Existing building	Source of approximate costs
Free-standing barriers	Stop logs 50 mm (100 × 100 cm)	Temporary	+	+	€650 (per 1 × 1 m)	€650 (per 1 × 1 m)	(Amari Austria 2017)**
	AquaFence (1.2 m)	Semipermanent	+	+	€350 (per m)	€350 (per m)	(Bjerkholt & Lindholm, 2007)
Levee/Berm	60 cm above ground	Temporary	+	+	€50 (per linear foot*)	€50 (per linear foot*)	(FEMA, 2014)
	120 cm above ground	Temporary	+	+	€90 per linear foot*)	€90 per linear foot*)	(FEMA, 2014)
	180 cm above ground	Temporary	+	+	€150 (per linear foot*)	€150 (per linear foot*)	(FEMA, 2014)
Floodwalls	60 cm above ground	Temporary	+	+	€80 (per linear foot*)	€80 (per linear foot*)	(FEMA, 2014)
	120 cm above ground	Temporary	+	+	€124 (per linear foot*)	€124 (per linear foot*)	(FEMA, 2014)
	180 cm above ground	Temporary	+	+	€175 (per linear foot*)	€175 (per linear foot*)	(FEMA, 2014)
External flood door	uPVC/fiber glass/metal external door with rubber gasket	Permanent	+	+	€820–€2,700	€820–€2,700	(Bowker, 2007)

2.5 | Emergency measures

Another option is temporary barriers, which work similarly to levees and floodwalls, but are completely removable and can be stored and reused after a flood event (FEMA, 2007). Examples can be seen in Table 6.

- *Tubes (air and water filled)*: These systems are temporary barriers, which are made of geomembranes or reinforced polyvinyl chloride (PVC) tubes. Tubes can either be air-filled or water-filled, the first needing anchoring using pins or weighted skirts, the latter using the dead load of water as a stabilization measure, both types are made of an impermeable membrane and need pumps to be filled (Ogunyoye et al., 2011).
- *Filled containers (permeable and impermeable)*: These temporary barriers can be filled with water or aggregates. They are either permeable or impermeable, and the dead load of the containers is used as means of stabilization (Ogunyoye et al., 2011). Permeable barriers are made of geotextiles or geosynthetic fabrics. Wire meshes, pins, and frames are used to stabilize them. The waterproofness of the measures is also dependent on the materials that are filled in the containers. Sandbags are a common example of this category, as seen in Figure 5 (Ogunyoye et al., 2011; Reeve & Badr, 2003). However, sandbags are quite low in effectiveness and can collapse or be overtopped during floods (Poussin, Botzen, & Aerts, 2015). In addition, the process of filling sandbags is time-consuming and labor-intensive. As sandbags are nonreusable and can often retain contaminants from sewage after flood events, they cause large disposal problems (Reeve & Badr, 2003). An advantage of these systems is that they can adapt to uneven terrain and solely require relatively unskilled labor. The impermeable

TABLE 6 Possible emergency measures, the approximate costs (€), the implementation type and their technical feasibility (+ technically feasible, ± technically partly feasible, − technically not feasible; n/a = information not available)

Measures	Measures: Detail	Temporary/ Permanent	Technical feasibility: New building	Technical feasibility: Existing building	Approximate cost: New building	Approximate cost: Existing building	Source of approximate costs
Tubes (air filled/ water filled)	Water filled (10 m)	Temporary	+	+	€1,200 (per 10 m)	€1,200 (per 10 m)	(AquaDam Europe Ltd, 2017)
	Air filled (10 m for 50 cm floodwater)	Temporary	+	+	€280 (per m)	€280 (per m)	(NOAQ 2017)
Filled containers (permeable/ impermeable)	Permeable: Sandbag (30x60 cm)	Temporary	+	+	€30 per piece	€30 per piece	(ERCO n.a.)
	Impermeable: Boxwalls(10 m set for 50 cm floodwater)	Temporary	+	+	€1,680 (16 boxes)	€1,680 (16 boxes)	(NOAQ 2017)

FIGURE 1 Newly built and elevated part of a single-family home in Steyr, Austria, which is prone to fluvial floods

FIGURE 2 Semiautomatic flood proof basement window in Graz, Austria. Once water levels rise in the basement shaft, the mechanism of the float will trigger the window to close. It is then opened manually again

FIGURE 3 Semipermanent window protection system in Neuburg an der Donau, Germany. Temporary elements (stop logs made of aluminum) will be implemented when warning of an upcoming flood in the Danube River is issued

FIGURE 4 Semipermanent door guard in Venice, Italy. Several houses in Venice have installed door guards as this example against high tides. These are installed before flood water rise and are often seen to be implemented when homeowners are not at home

option is usually made of polyester, polyethylene, or plastic. Such containers are filled with water or other aggregates to create stability. Compared to sandbags, impermeable containers are rather rigid and do not adapt to uneven terrain (Ogunyoye et al., 2011).

FIGURE 5 Sandbags used as temporary emergency measures (Source: Austrian Armed Forces, 2005)

It has to be considered however that some dry flood-proofing measures and temporary barriers are only suitable for flood events with longer lead times in order for the measures to be properly installed. In headwater catchments of mountain areas or during pluvial floods lead times are often not sufficient to implement temporary measures before damage is caused (Kreibich et al., 2015).

2.6 | Other mitigation measures

- *Anchorage of oil tanks*: In case of a flood event, damages to oil tanks and the consequent leakage can lead to property contamination and pollution (Thieken, Müller, Kreibich, & Merz, 2005). Such tanks have to be secured from uplift using proper anchorage, which can be realized in both existing buildings and new structures. In general, it becomes apparent that measures which are integrated during the planning process of a new building will be more cost-effective than if they are implemented retrospectively for buildings already existing. Temporary measures can always be implemented retrospectively, whereas measures such as elevation and sealing building openings/walls are costly and technically demanding to add in retrospect. It becomes evident that only a combination of several PLFRA measures can provide sufficient protection. A study by de Ruig, Haer, de Moel, Botzen, and Aerts (2019) demonstrated that a combination of dry flood-proofing and elevation could serve as the most cost-efficient solution for homeowners. However, the cost-efficiency of PLFRA measures strongly depends on the flood probability, the type of house and type of flood as well as on the scale.

3 | INDIVIDUAL MOTIVATIONS TO IMPLEMENT PLFRA MEASURES

Even if a variety of different PLFRA measures exists, the question of whether or not to invest in such measures and to implement them is challenging for homeowners. PLFRA measures are often built on basis of individual experiences and perception (Holub & Hübl, 2008). Therefore, implementing PLFRA measures demands self-responsibility on the side of the affected homeowners as these measures are largely voluntary (Kreibich et al., 2015). Implementing PLFRA measures focuses mainly on the individual household level because technical protection schemes are often understood as collective flood risk management strategies. The implication is that policy documents and academic research center on individuals and only in rare cases on collective actions and activities (Burns & Slovic, 2012; Seebauer, Ortner, Babcicky, & Thaler, 2019; Thaler & Seebauer, 2019). Consequently, the critical question focuses on what drives/motivates private people to adapt to flood hazards. In the literature, there is a wide range of potential trigger mechanisms that might (or not) encourage individual risk behavior (Bamberg et al., 2017; Van Valkengoed & Steg, 2019; Werg et al., 2013). Apart from financial incentives, the willingness of individuals to invest into preparedness is framed by different underpinnings, such as neighborhood effects, education, age and proximity to the rivers, and so on (Bamberg et al., 2017; Van Valkengoed & Steg, 2019). The largest group of studies focuses on cognitive, socioeconomic, and situational elements to understand the motivations of individuals (Koerth, Vafeidis, & Hinkel, 2017). Various studies have used diverse theoretical models based on different disciplines, such as psychology, behavioral economics, or disaster risk reduction (Van Valkengoed & Steg, 2019). The following sections will discuss several concepts which explain theoretical models within individual preparedness.

3.1 | Theoretical concepts to explain individual preparedness

Overall, we observe two main directions within preparedness theory: (a) coping capacity mainly driven by psychological variables and (b) socioenvironmental variables based on psychological and social processes. This section will highlight these two directions seen in different models and theories.

The protective action decision model (PADM) is part of the judgment and decision-making stage model, where it provides theoretical concepts in explaining individual preparedness through a framework to assess and analyze factors influencing individual responses to flood hazards (Lindell & Perry, 2004). People decide if they need to undertake any actions and the time framework of implementation. Consequently, the model assumes that individuals exhibit three main developments in response to flood hazards: (1) search for additional information; (2) undertake actions to protect themselves; or (3) undertake actions to reduce their psychological stress regarding future flood hazard events (Lindell & Perry, 2004). PADM shows the critical threshold of information processing in disaster risk reduction. However, a disadvantage of the model is the assumption that people already have an understanding of natural hazards processes and high interest in information about the hazard.

Various studies—especially from Europe—focus on the protection motivation theory (PMT) by Rogers (1975, 1983) to explain individual response to flood hazards (Babcicky & Seebauer, 2019; Bamberg et al., 2017; Bubeck, Botzen, Laudan, Aerts, & Thieken, 2018). PMT distinguishes between two main cognitive stages of individuals: (1) threat appraisal describes how people feel about flood risk and includes two main variables—perceived probability and consequences of a future flood event and (2) coping appraisal. Coping appraisal describes the various cognitive processes of individuals when they evaluate possible responses to the threat and their own abilities to undertake actions as a means of reducing their own vulnerability (Babcicky & Seebauer, 2017, 2019; Bamberg et al., 2017; Bubeck, Botzen, Kreibich, & Aerts, 2013; Grothmann & Reusswig, 2006). Coping appraisal involves three main components: (1) response efficacy (how individuals consider adaptive measures for disaster risk reduction); (2) self-efficacy (how individuals consider themselves able to implement PLFRA measures); and (3) response cost (what individual resources—time, finances, and emotions—are available for the implementation) (Babcicky & Seebauer, 2019; Bubeck et al., 2013; Grothmann & Reusswig, 2006). In sum, individuals have two options: (1) undertaking proactive protection behavior, which goes in the line with high threat and coping appraisal (protective response); or (2) nonprotective response, wherein individuals show high threat appraisal but low or no coping appraisal. Following a nonprotective response, people tend toward wishful thinking and denial of the problem. This entails that there may be negative emotional fallout during future events, however, they do not undertake actions to reduce possible damages (Rogers & Prentice-Dunn, 1997). A similar theoretical explanation is the regulatory focus theory (RFT). RFT focuses on the question of how the motivation of individuals fits into achieving their goals. RFT assumes that two coexisting motivational classifications outline individual decision, mainly: (1) prevention-motivated individuals, individuals seek the status-quo and (2) promotion-motivated people, who aim to improve their well-being (Higgins, 1997, 1998). Botzen, de Boer, and Terpstra (2013) used RFT to assess the effect of risk communication on individuals' interests in protecting themselves.

The second group of preparedness theories, such as the social amplification of risk framework (SARF), affirms that individual behavior is also influenced by sociocultural and institutional settings (Kasperson et al., 1988). SARF means to understand individual risk behavior as the interconnection between social processes and hazard events, wherein individual response arises from an institutional rule-system, governance arrangement, social protest, interests, and relationships. Therefore, individual behavior interacts with various psychological, social, institutional, and cultural processes. Nevertheless, the holistic framework with all its complexities makes it hard to prove on empirical data. Like the SARF, the community engagement theory (CET) integrates individual, social, and institutional variables to understand individual behavior. It analyzes the functional characteristics of the interconnections between members of the community (Paton, 2008, 2013). An important outcome is the empowerment of individuals to engage in local (community) risk management strategies and trust bottom-up agencies (Kerstholt et al., 2017; Paton, 2008).

A similar approach is the theory of reasoned action (TRA) (Ajzen & Fishbein, 1980). The main assumption of the TRA is that individuals are motivated to conduct an activity and the model places importance on individuals' aim to perform. The model explains the connection between the intended behavior of individuals and the individuals' pre-existing attitudes based on social processes such as norms. Nevertheless, homeowners might be highly selective ("bubble") in accessing information channels they use for their daily lives, which heavily influences the content of the message (Ajzen & Fishbein, 1980; Earle, 2010; Kasperson et al., 1988; Lo, 2013). Hereby, different channels such as social media, face-to-face, or expert advice are used (Terpstra, Zaalberg, Boer, & Botzen, 2014).

In general, the different preparedness theories focus on a wide range of diverse assumptions and perspective to understand and to assess the individual or collective preparedness to flood hazard events. The theories have some power to explain the preparedness of individuals or community. However, the theoretical concepts mainly focus on preparedness rather than emergency or recovery, in which we hardly observe theoretical concepts. Additionally, key focus lies on individuals instead of collective actions. Further questions arise if the theoretical concepts, which mainly root in psychological theories, are transferable within cross-cultural settings.

3.2 | Explanatory variables used in preparedness theories

The different theories discussed in this paper used a wide range of variables to explain the motivation of individuals to undertake (or not) protective actions such as PLFRA measures. Factors might be: socioeconomic (e.g., age, income, and ownership), cognitive (e.g., experience, knowledge, and responsibility), experience, or personal knowledge (e.g., personal experiences), which are also the most widely used variables in recent studies (Babcicky & Seebauer, 2017; Botzen, Aerts, & van den Bergh, 2009; Koerth et al., 2017). In the majority of studies, variables were used in combination to increase the power of explanations (Bichard & Kazmierczak, 2011; Ge, Peacock, & Lindell, 2011; Kellens, Zaalberg, & De Maeyer, 2012; Reynaud, Aubert, & Nguyen, 2013). However, only few studies have combined personal and nonpersonal variables (Baker, 2011; Botzen et al., 2009). Many variables have a bidirectional effect (positively/negatively or strong vs. weak correlated) in evaluating the personal adaptive behavior (Koerth et al., 2017). Some explanation for this challenge might include the small sampling of variables used in past studies, small sampling size, misinterpretation of correlation, failure control before and after a flood hazard event, missing of longitudinal research, or correlation being positive, but very small (Bamberg et al., 2017; Koerth et al., 2017; Van Valkengoed & Steg, 2019; Weinstein, Rothman, & Nicolich, 1998). In fact, the effects of each factor on individual behavior are quite complex and sometimes hazardous; trigger mechanism are often case study specific as different sociocultural and individual circumstances influence individual behaviors (Bubeck et al., 2018; Fuchs, Röthlisberger, Thaler, Zischg, & Keiler, 2017; Kellens, Zaalberg, Neutens, Vanneuville, & De Maeyer, 2011; Logan, Guikema, & Bricker, 2018; Molua, 2009; Poussing, Botzen, & Aerts, 2014). In particular, sociodemographic variables show different directions. Elderly people might be more open to implement adaptive measures, considering they own the property or have more financial savings than younger people, who often need a mortgage to buy their homes. However, studies show that elderly people are less willing to invest in their property. Similar results are observable regarding experiences related to adaptive behavior. Some academic research indicates the positive effects of experiences, but some publications cannot confirm this hypothesis (Bubeck et al., 2018; Demuth, Morss, & Lazo, 2016; Fuchs, Röthlisberger, et al., 2017; Kellens et al., 2011; Terpstra & Lindell, 2013). In addition, insurance is generally considered a private mitigation option even if it does not directly reduce vulnerability. However, people can be unwilling to purchase insurance against floods if they are not rewarded by reduced premiums when they make the effort to lower their vulnerability. Moreover, insurance can give biased information by encouraging building in flood-prone areas when premiums are not appropriately calculated according to risk (Newman et al., 2017). In terms of which type of PLFRA measures people implement (Section 2), personal competences and kind of PLFRA measures can stimulate local adaptation behavior (Thieken, Kreibich, Müller, & Merz, 2007; Van Valkengoed & Steg, 2019). Not surprisingly, homeowners usually implement (or are willing to implement) low-cost PLFRA measures (Bubeck et al., 2013; Bubeck, Botzen, Kreibich, & Aerts, 2012).

First meta-analyses allow us to provide a better picture of the effect of factors (Bamberg et al., 2017; Van Valkengoed & Steg, 2019). The significance and effect of each factor varies between studies. Van Valkengoed and Steg (2019) report that mainly negative effects and outcome efficacy show a strong relationship in terms of changing individual behaviors. Other factors, such as risk perception, belief in climate change, perceived responsibility, or social norms show a small-to-moderate impact on individual behavior. At the same time, their results provide examples of the current limitations of published studies, especially in terms of the high heterogeneity in effect sizes. Interestingly, Bamberg et al. (2017) and Van Valkengoed and Steg (2019) only partly support the roles of past flood experiences in the development of adaptive behavior among individuals. The results of the meta-analysis showed that experiences on previous flood events are positively associated with adaptive behavior, but the results are nonsignificant-to-small in terms of their effect on the general heterogeneity among literature. Koerth, Vafeidis, Hinkel, and Sterr (2013) highlighted the importance of the careful interpretation of results, as their results on experiences on past flood events showed a high standard error. Perhaps this is because past experiences heavily depend on how to measure damage, as well as on how flood memories are remembered and how other circumstances influenced the results, such as whether one experienced a flood event as a child or adult (McEwen, Garde-Hansen, Holmes, Jones, & Krause, 2017; Sharma & Patt, 2012; Van Valkengoed & Steg, 2019).

4 | CONCLUSION

As losses of flood hazards are rising globally (Munich Re, 2018), it is apparent that risk management strategies must be improved. By making homes more resilient toward facing the challenges of hazards, the vulnerability to future flood hazard events can decrease. With respect to the built environment, there is dependence on the geometry and design of the building, the mechanical properties emerging from construction materials used (Mazzorana et al., 2014; Sturm et al., 2018a, 2018b). It has been shown that several PLFRA measures are effective and efficient to complement public protection measures (Kreibich et al., 2015). Nevertheless, none of the described measures can fully protect a building from possible damages. A way of achieving an accepted level of risk reduction is by implementing PLFRA measures in combination with further flood alleviation schemes (Ward et al., 2017). Implementing measures is in several cases a costly activity and sometimes requires expert support. Nevertheless, there are PLFRA measures, which can be implemented solely by the homeowners. Kreibich et al. (2011b) showed that large investments in PLFRA measures, such as waterproofing cellars, are more economically reasonable in high-risk areas. Small investments, such as using sandbags, are more reasonable in low-risk areas. Financial incentives, such as those, which subsidize costs of programs, aimed at encouraging homeowners to undertake mitigation measures might mitigate flood losses at the local level and can change behaviors. However, insurance can give an unhelpful signal by encouraging to build in at-risk areas when premiums are not properly calculated (Newman et al., 2017).

Moreover, the responsibility of engaging individuals raises serious questions in terms of social justice and individual well-being (Thaler, Zischg, Keiler, & Fuchs, 2018; Werg et al., 2013). Individual risk behavior relies on an active and financially robust household as homeowners largely have to fund and maintain the PLFRA measure. There is a clear challenge regarding a large amount of households which can neither afford (financially, personal, legally) nor are willing to engage in adaptive strategies. Consequently, adaptive behavior is not always viewed as politically feasible by public administrations (Patterson et al., 2018; Thaler et al., 2018). Nevertheless, stronger engagement with individuals in flood risk management also demands a new role of public administration (shifted from engineering knowledge toward a stronger focus on project management and communication knowledge), also in terms of conducting further actions in climate change mitigation strategies (Demski, Capstick, Pidgeon, Sposato, & Spence, 2017; Scolobig, Prior, Schröter, Jörin, & Patt, 2015).

This overview highlights that human behavior and adaptive actions are crucial in response to potential future changes in the frequency of flood hazard events. Nevertheless, this approach is highly challenging: the variance of different influencing factors is often not linear, and decisions on self-responsibility are complex, uncertain and often part of dealing with biased expectations (Besolo, Steinberg, & Gant, 2017; Grothmann & Reusswig, 2006; Meyer, 2012). Individuals and communities need to be more active in flood risk management. A central aspect is that policy makers allow homeowners to be involved in flood risk management process and if possible in a collective manner through grassroots organizations (Seebauer et al., 2019). However, the requested behavioral change is far more complex and difficult, but in many cases feasible as our overview highlighted. Thus, a comprehensive summary of costs, efficiency, and applicability of PLFRA measures should be available and communicated to homeowners living in flood prone areas, in order to support their decision-making process.

As seen, there are several concepts and theories, which aim at explaining the potential implementation of PLFRA measures. However, there is not one sole, overarching theory, which can clarify all choices and decisions made by homeowners. Additionally, the efficiency of PLFRA measures is dependent on the situation of every individual property, making a one-fits-all concept impossible.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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