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COST-EFFECTIVE MITIGATION STRATEGY DEVELOPMENT FOR FLOOD PRONE BUILDINGS

Literature review of mitigation strategies

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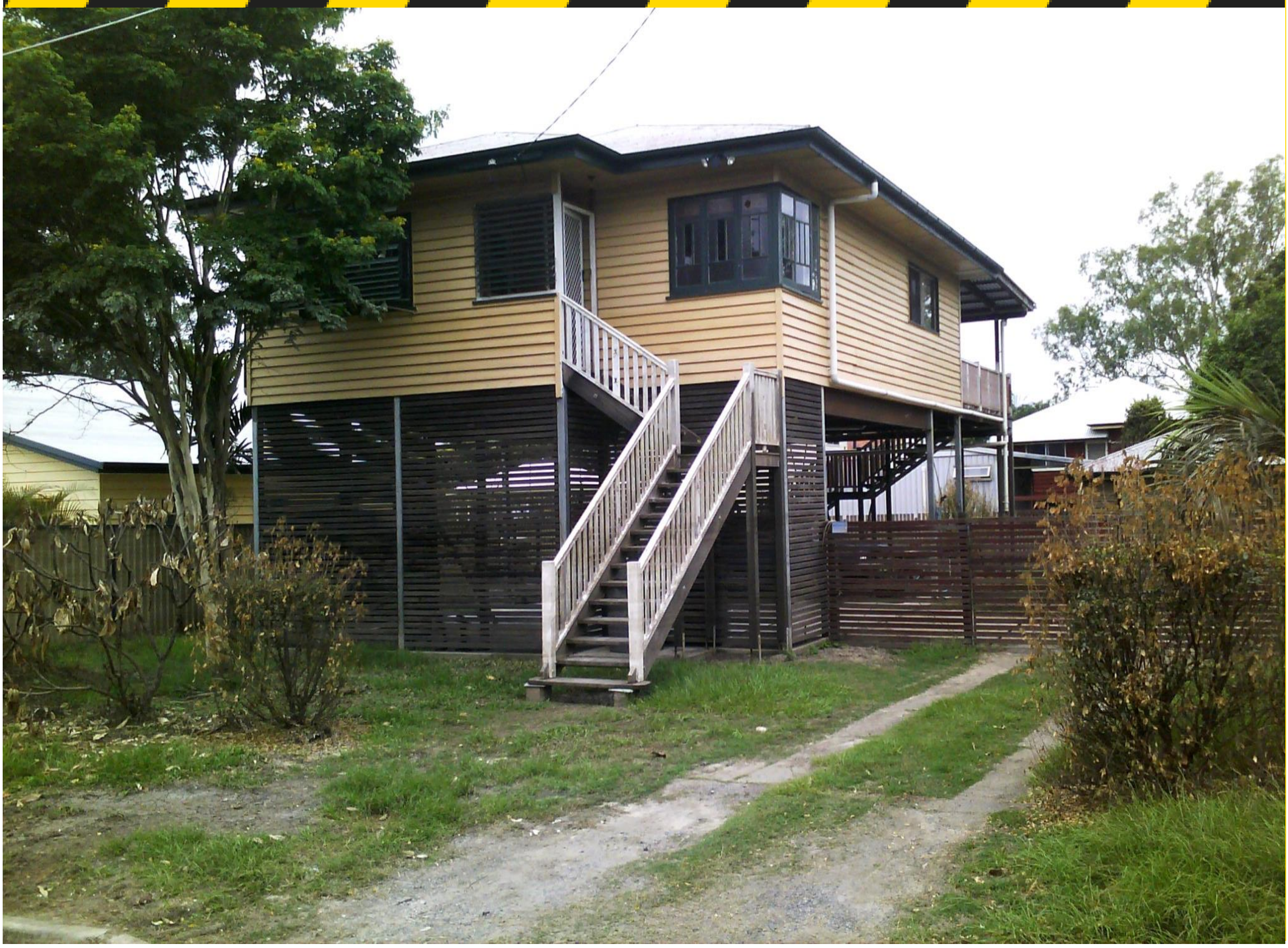

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EXECUTIVE SUMMARY

This report forms part of the output to a research project titled 'Cost effective mitigation strategy development for flood prone buildings' within the Bushfire and Natural Hazards Cooperative Research Centre (BNHCRC, 2015). The motivation for this project arises from the experience and observations during the recent flooding in Australia in 2011, 2013 and 2015, which caused widespread devastation in Queensland. A fundamental reason for this damage was inappropriate development in floodplains and a legacy of high risk building stock in flood prone areas. Although the vulnerability and associated flood risk is being reduced for newer construction by adopting new standards (ABCB, 2012), building controls and land use planning, the vulnerability associated with existing building stock remains. Therefore, the existing vulnerable buildings contribute disproportionally to overall flood risk in many Australian catchments. The BNHCRC project aims to address this issue and is targeted at assessing mitigation strategies to reduce the vulnerability of existing residential building stock in Australian floodplains.

As a first step to achieving this goal within this project a building schema has been developed to categorise the Australian residential building stock (Maqsood et al. 2015). The next step is to conduct a literature review of mitigation strategies developed nationally and internationally and this report presents the findings of this research component. The review will help to evaluate the strategies that suit Australian building types and typical catchment behaviours and hence may be adopted in Australia. Strategies have been developed for different types of floods and the adoption of a particular strategy depends upon the characteristics of flood hazard and building stock along with any mitigation incentives and associated cost benefit analysis. This report discusses the commonly used strategies and summarises the advantages and disadvantages of each of them. The review categorises mitigation strategies into the following categories:

- Elevation
- Relocation
- Dry floodproofing
- Wet floodproofing
- Flood barriers

Elevation is traditionally considered to be an easier and effective strategy and is the one which generally result in incentives such as a reduction in insurance premiums (Bartzis, 2013). However it becomes difficult to execute for slab-on-grade structures. Relocation is the surest way to eliminate flood risk if relocated outside the floodplain but, as in the case of elevation, it becomes more difficult to implement for heavier and larger structures. Dry floodproofing and flood barriers are efficient only in shallow low velocity hazard areas and are generally not recommended in deep fast flowing waters. Wet floodproofing is suitable in low to moderate depths of water with a inundation duration of not more than a day.

In future years (2015-2019) of this project, each mitigation strategy will be evaluated and costed through engagement of professional quantity surveyors. Strength degradation of common building components (materials, structural systems) due to wetting and subsequent drying will be assessed through experimental testing. Cost benefit analyses will be conducted to determine optimum retrofit strategies for selected residential building types within a range of catchment behaviours. The result will be an evidence base to inform decision making by government and property owners on the mitigation of flood risk by providing information on the cost effectiveness of different mitigation strategies and an optimal solution for different cases of building and catchment types.

INTRODUCTION

White (1945) wrote that floods were acts of God but flood losses were largely acts of man. However, due to major developments in floodplains which are acts of humans, the floods are no longer considered as acts of God as humans played a key role in changing the land use (Green et al. 2011). Globally, floods cause tremendous damage with loss of life and property. An analysis of global statistics conducted by Jonkman (2005) showed that floods (including coastal flooding) caused 175,000 fatalities and affected more than 2.2 billion people between 1975 and 2002. In Australia, floods cause more damage on an average annual cost basis than any other natural hazard (HNFMSC, 2006). The fundamental causes of this level of damage and the key factors contributing to flood risk, in general, is the presence of vulnerable buildings constructed within floodplains due to ineffective land use planning.

The Bushfire and Natural Hazards Collaborative Research Centre project entitled 'Cost-effective mitigation strategy development for flood prone buildings' (BNHCRC, 2015) will examine the opportunities for reducing the vulnerability of Australian residential buildings to flood. It will address the need for an evidence base to inform decision making on the mitigation of the flood risk posed by the most vulnerable Australian building types and complements parallel BNHCRC projects for earthquake and severe wind. This project will investigate methods for the upgrading of existing residential building stock in floodplains to increase their resilience in future flood events. It is important that the latest research and economically optimum upgrading solutions are applied to existing buildings so the finite resources available can be best used to minimise losses, decrease human suffering, improve safety and ensure amenity for communities.

The project will make assessments of the reduction in damage loss that will ensue from the implementation of a range of mitigation measures assessed by the project. This research requires the context of a building vulnerability classification, or schema. Maqsood et al. 2015 provides details of the building schema developed within this project which divides a building into its major components (i.e. foundation, ground floor, upper floors (if any) and roof) enabling the vulnerability of each of those components to be assessed separately. This new approach facilitates the development of vulnerability models for taller buildings, buildings with basements, buildings with mixed usages and those with different construction material used at different floor levels.

This report presents the outcome of the next project activity: a literature review of mitigation strategies. The review has considered literature available through peer-reviewed journals, international conferences and research reports. Finally, a decision making process is discussed which presents the factors which are should be taken into consideration when deciding to undertake a particular mitigation strategy.

PROJECT BACKGROUND

Recent events in Australia (2011, 2013 and 2015) highlight the vulnerability of housing to flooding which originates from inappropriate development in floodplains. While there is now a construction standard published by the Australian Building Code Board (ABCB, 2012) for new construction in flood prone areas, there is a large proportion of existing building stock that has been built in flood prone areas across Australia (HNFMSC, 2006). The Australian Government has developed a national strategy which defines the roles of government and individuals in improving disaster resilience (NSDR, 2011). The Australian Government also emphases the responsibility of governments, businesses and households on assessing risk and taking action to reduce the risk by implementing mitigation plans (Productivity Commission, 2014).

An in-depth understanding of the effects of floods is required for the assessment of risk and the development of mitigation strategies, particularly in the context of limited financial resources. In this respect, reliable information about the costs and benefits of mitigation are crucial to inform decision-making and the development of policies, strategies and measures to prevent or reduce the impact of flood.

The objective of this project is to provide an evidence base for two target groups to inform their decision making process around mitigation against flood risk: government and property owners. Federal, State/Territory and local governments have an interest in loss estimates arising from past or future events and require vulnerability information to support several objectives including decision making concerning the allocation of funding and risk management. Property owners are also interested in vulnerability and mitigation assessment to know the potential risk to their properties due to floods and make decisions on undertaking mitigation measures to reduce risk and possibly insurance premiums (Meyer et al. 2012).

The potential risk due to flood and mitigation benefits can be assessed by following a standard approach consisting of four basic steps (Messner et al. 2007; Merz et al. 2010; Green et al. 2011; Maqsood et al. 2013):

1. Classification of building stock into typical building types.

2. Exposure analysis including estimating the number of properties of each typical building type and assessing their asset value.

3. Loss assessment by relating the relative damage of building to flood severity (e.g. depth) by using vulnerability models (stage-damage functions).

4. Selection and implementation of optimum mitigation measures with the aid of cost benefit analysis.

Vulnerability models can be developed in three ways: by following an analytical approach, by using empirical data or based on expert judgement. Geoscience Australia (GA) followed each of these approaches in developing flood vulnerability models (Wehner et al. 2012, Maqsood et al. 2013, 2014). To facilitate the development of these models GA conducted a number of post-disaster surveys to assess building damage due to inundation. The surveys consisted of street view image capture to obtain an overview of damage within the flood extents; foot surveys capturing detailed building attributes and damage incurred (see Figure 1); and postal surveys to assess building repair costs and social impacts due to floods (Maqsood et al. 2014).

The data captured during surveys serves to constrain the analytical approach as it reflects real losses and reduces the uncertainty associated with the assessment of which components of buildings require repair, the nature of repair and the cost of repair (Merz et al. 2010, Mason et al. 2013). Generally vulnerability models have considerable uncertainty, however it is rarely quantified during flood risk assessment (Merz et al. 2004; Apel et al. 2008, 2009; Merz and Thieken, 2009; de Moel and Aerts, 2010; Bubeck et al. 2011; de Moel et al. 2012). Survey data can be used to calibrate the analytical results to provide a better understanding of the variability in the vulnerability models.

The information on vulnerability and the factors/parameters affecting vulnerability is fundamental to evaluating mitigation strategies to reduce future losses. Therefore, this BNHCRC project systematically develops information about building types in Australia, their vulnerability and possible mitigation measures associated to different building types to reduce their vulnerability. To date, a building classification schema has been developed to categorise Australian residential buildings into a finite set of typical building types (Maqsood et al. 2015). This report provides a literature review of mitigation strategies. In future years (2015-2019), building on this report each mitigation strategy will be evaluated and will be costed through engagement of professional quantity surveyors. Cost benefit analyses will be conducted to determine optimum retrofit strategies for selected building types applicable to a range of catchment behaviours.

The result will be an evidence base to inform decision making by government and property owners on mitigation of flood risk by providing information on the cost effectiveness of different mitigation strategies and an optimal solution for different cases of building and catchment types.

Figure 1. Examples of building damage recorded after 2011 Southeast Queensland flood

FLOOD CHARACTERISTICS AND BUILDING DAMAGE

To understand how floods can damage houses and to evaluate and implement any mitigation measures, there is a need to first understand the flood characteristics. Furthermore, the impact of these characteristics on buildings and damage which may occur due to a single characteristic or combination of these characteristics needs to be assessed (Kelman and Spence, 2004). Key flood characteristics are discussed below.

DEPTH

Flood depth is the depth of the water above the surface of the ground or finished floor depending upon the selection of reference point. The depth of flooding is the most important parameter primarily because water damages building fabric and fit-outs and exerts pressure on structural components of a building (Thieken et al. 2005). The pressure exerted by still water is called hydrostatic pressure and is caused by the weight of the water, so it increases linearly as the depth of the water increases (Kelman, 2002). If water is allowed to enter the house, the hydrostatic pressures on both sides of the walls and floor equalise and thus less likely to cause building failure (FEMA, 2008c). It is also an important characteristic to consider as most of the flood studies and vulnerability models consider it as a primary hazard parameter and are often based solely on this parameter.

FLOW VELOCITY

Flow velocity is the speed at which water moves and is usually measured in metres per second (m/s). Velocities can reach 2 to 3 m/s during floods and in some cases may be greater. In flowing water in addition to the hydrostatic pressure, the pressure of moving water (referred to as hydrodynamic pressure) is applied to the building which can result in severe building damage (Kelman, 2002; Escarameia et al. 2006). Higher velocities can also cause erosion and scouring around buildings foundations.

The combined effect of depth and velocity is critical to the safety of people and buildings and can result in loss of human stability and consequent drowning (FEMA, 2014; Jonkman and Penning-Rowsell, 2008; Jonkman et al. 2005; Jonkman et al. 2008; Penning-Rowsell et al. 2005; Asselman and Jonkman, 2007; Kelman, 2002). Smith and McLuckie (2015) presented a combined hazard curve which categorises flood hazard into six classes based on safety of vehicles, people and buildings when interacting with floodwater (Figure 2).

A study done by Smith et al. 2014 proposed thresholds that relate building stability to flood hazard and its suitability as shelters during and after floods (Figure 3). The proposal is included in the technical flood risk management guideline document produced by the Australian Government (NFRAG, 2014; McLuckie et al. 2014). Further to proposing hazard thresholds, a number of studies used a combination of depth and velocity as a hazard parameter while developing vulnerability models and conducting impact assessments (McConnell and Low, 2000; Dale et al. 2004; Schwarz and Maiwald, 2008; Kreibich et al. 2009; Pistrika and Jonkman, 2010, Maiwald and Schwarz, 2012). However, velocity is considered to be a more difficult hazard parameter to constrain and therefore requires additional efforts to be ascertained during a flood event.

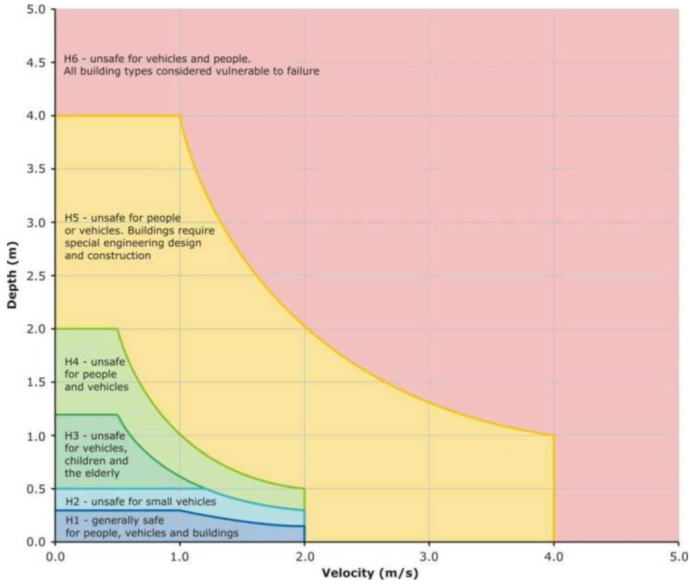


Figure 2. Flood hazard curve (Smith et al. 2014; Smith and McLuckie, 2015)

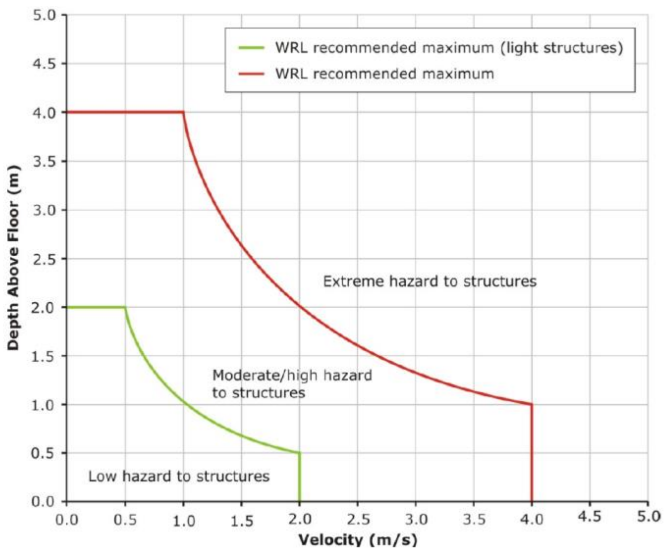


Figure 3. Thresholds for building stability in floods (Smith et al. 2014; McLuckie et al. 2014)

FREQUENCY

In conducting flood studies, the flood that has a one percent probability of being equaled or exceeded in any year is generally considered as a Design Flood. Floor heights for residential buildings are generally based on the Design Flood level along with certain value of freeboard (usually 300mm to 500mm). It should not be understood to be a flood that happens exactly once every 100 years nor does it imply that once a 100-year flood occurs there is a reduced chance of another 100-year flood occurring in the near future (FEMA, 2014). Moreover, the 100-year average recurrence interval flood is not the limit of flood severity. Many communities have suffered damage from rarer events which exceeded design levels and resulted in significant amount of loss. Frequent flooding may render some of the mitigation strategies infeasible due to the cumulative wear and tear effects of recurring inundation (FEMA, 1993).

RATES OF RISE AND FALL

These rates are usually expressed in terms of metres per hour. Rate of rise is an important parameter which informs warning time of an approaching flood. Rates of rise and fall are also important because of the effect on unbalanced hydrostatic pressure which is created due to differential water levels inside and outside of a building which, as mentioned earlier, is dangerous for building stability (Asselman and Jonkman, 2007; Jonkman et al. 2008). Tests conducted by Kelman and Spence (2003) reported that walls of unreinforced masonry buildings in the UK fail when the flood depth differential between the inside and the outside is approximately 1 to 1.5m.

DURATION

Duration is the time that a flood lasts in a catchment or how long it takes for the creek or river to return to its normal level. Duration of flood is important as longer exposure to floodwater increases the severity of damage including the deterioration of structural components, interior finishes and other contents of a building (FEMA, 1993; FEMA, 2014).

DEBRIS IMPACT

Floodwater can carry objects such as trees, portions of buildings damaged due to flood and cars which can exacerbate damage when they impact structures. The force of debris impact depends on the shape, size, weight, velocity and orientation of impact (HNFMSC, 2006). The impact can be from outside the building (e.g. a car or tree trunk) or from inside the building (e.g. from a sofa or table) (Kelman and Spence, 2004). Debris impact generally results in greater property damage, higher clean-up cost and longer recovery times than just the flood water without debris.

LITERATURE REVIEW OF MITIGATION STRATEGIES

Although recent improvements in building controls and regulations have made new homes less prone to flood damage, many existing homes continue to be damaged by flooding, repeatedly in some instances. Mitigation or retrofitting involves making changes to an existing building to protect it from flooding (USACE, 1993; FEMA, 2014). A literature review has been conducted to identify mitigation strategies used in several countries and for various severities of flooding. The review has considered literature available through peer-reviewed journals, international conferences and research reports. Following this review the applicability of these strategies will be evaluated in an Australian context and costed.

Bouwer et al. 2011 classified the different types of retrofit or mitigation measures into nine basic categories. The classification is presented in Table 1 and was based on a distinction between mitigation measures that focus on hazard reduction and those that focus on vulnerability reduction. Furthermore, the measures were distinguished on the basis of the main approach followed such as technical or engineering solutions, legal, communication or economic instrument.

Another widely used broader classification of mitigation measures is based on whether the strategies utilise engineering and administrative methods to reduce flood risk or modify the flood characteristics and human occupancy of the flood plain. These are broadly divided into structural and non-structural approaches (Brody et al. 2010) or hard and soft measures (Productivity Commission, 2014).

Hard or structural approaches are generally based on engineering interventions to control floods or protect communities by building dams, retention basins and levees. While there are benefits of structural approaches to flood mitigation there are limitations. For example when flooding exceeds the design capacity of a structure the result is significantly higher damage (Larson and Pasencia, 2004). Levees which can raise the level and velocity of water by constricting the waterway and the natural floodplain result in shortened flooding time and greater flooding downstream (Birkland et al. 2003). Furthermore, structural measures (e.g. a levee) may bring a false sense of security to the community which may result in a disaster when the levee is overtopped in a flood event greater than the design level of the levee. Lastly, structural measures can be very costly (Productivity Commission, 2014).

In light of the above mentioned limitations of structural approaches to flood mitigation, authorities and researchers are increasingly evaluating and adopting soft or non-structural approaches to tackle the flood risk issue. These strategies include raising awareness and educating the community about their flood risk, improving land use planning, better preparation, putting in place emergency and recovery policies, flood warning and forecasting and introducing insurance plans (Brody et al. 2010; Productivity Commission, 2014). However, as opposed to structural measures, the quantification of the reduced impacts due to non-structural measures is difficult. This is considered its major limitation that results in non-structural measures seldom being carried out.

The projects which are based on Cost-Benefit Analysis (CBA) of different mitigation options mostly utilise engineering based structural solutions to justify the approval process. CBA is generally used to aid decisions about allocation of budget. One of the biggest strengths of CBA is that most costs and benefits are expressed in monetary terms and, therefore, enable a direct comparison of investment and related benefits (Productivity Commission, 2014). CBA is well suited for governments as it is based on a rigorous analysis which ensures consistency in assessment both within and between mitigation options. An optimum solution can then be determined in a transparent manner (Bouwer et al. 2011).

An alternative to CBA is Multi-Criteria Analysis (MCA) which is well suited to a decision making process in a situation where a number of stakeholders are involved e.g. in a workshop environment. The main advantage of MCA is that it provides an explicit method of taking account of investment impacts that are not easily assigned a monetary value and are often called intangibles (FHRC, 2014). Through MCA stakeholders can weigh, argue, debate and negotiate the mitigation options and then arrive at a consensus on the optimum solution. Different weighting schemas can also be used to evaluate the impact of mitigation measures on the reduction of flood risk in a catchment.

This BNHCRC project is focused on residential structures with an aim to reduce structural vulnerability. It will utilise CBA as a tool to select the best mitigation options which can be evaluated in monetary terms. The following sections provide an overview of mitigation strategies (stricto sensu as per Table 1) that have been implemented in Australia and internationally to reduce the vulnerability of housing to floods.

TABLE 1: CATEGORIES OF MITIGATION MEASURES (BOUWER ET AL. 2011)

Category	Main goal	Main approach	Examples
Management plans	Vulnerability reduction	Legislation, communication, Economic instruments	Spatial planning, adaptation strategies
Hazard modification	Hazard reduction	Technical, engineering	Retention areas
Infrastructure	Hazard reduction	Technical, engineering,	Reservoirs, dams, levees
Mitigation measures (stricto sensu)	Vulnerability reduction	Technical, engineering, economic instruments	Elevation, dry floodproofing, wet floodproofing, relocation
Communication (in advance of events)	Vulnerability reduction	Legislation, communication	Education, awareness
Monitoring and early warning systems (just before events)	Hazard reduction and vulnerability reduction	Technical, engineering, communication	Flood forecasting
Emergency response and evacuation	Vulnerability reduction	Technical, legislation, communication	Evacuation, response and recovery operations
Financial incentives	Vulnerability reduction	Legislation, communication, economic instruments	Government and insurance incentives
Risk transfer	Vulnerability reduction	Legislation, economic instruments	Insurance mechanisms, compensation

ELEVATION

Elevation of a structure is one of the most common mitigation strategies which aims to raise the lowest floor of a building above the expected level of flooding. This can be achieved, for example, by extending the walls of an existing structure and raising the floor level; by constructing a new floor above the existing one; or through raising the whole structure on new foundations (walls, piers, columns or piles) as shown in Figure 4 and Figure 5.

Elevation by extending the walls is normally used in low to moderate water depth with low flow velocity. Elevation on piers is generally done in shallow low velocity conditions and with piers made of brick or cast-in-place concrete. Elevation on columns is done in moderate depths and velocities with columns of wood, steel or reinforced concrete with cross bracings. Elevation on piles is done in deep and high velocity conditions where scouring is expected to occur with piles made of wood, steel or reinforced concrete with cross bracings (USACE, 1993). One advantage of elevating the structure on columns and piles is that the flow of floodwater is not restricted as in the case of walls. Furthermore open areas created under the structure by this approach can be used for parking or storage purposes (FEMA, 2008a).

The technical considerations that need to be taken into account in raising buildings are structure type, construction material, foundation type, building size, flood characteristics and other hazards. Other factors to take into consideration when elevating existing structures are additional loading on foundations, additional wind forces on wall and roof systems and any seismic forces (FEMA, 2012).

Generally the least expensive and easiest building to elevate is a low-set single storey timber frame structure (USACE, 2000). The procedure becomes complicated and expensive when other factors are included such as a slab-on-grade construction, walls of masonry or concrete or a multi-storey building (USACE, 1993). Currently elevation is one of the strategies which result in incentives from the insurance industry in the form of reductions in annual premiums for flood insurance (Bartzis, 2013). An analysis conducted by FEMA (2010) showed that house owners can break even on their investment in adopting this mitigation strategy in little over five years due to reductions in their flood insurance premiums. Table 2 provides some of the advantages and disadvantages of the building elevation strategy.

TABLE 2: ADVANTAGES AND DISADVANTAGES OF BUILDING ELEVATION (FEMA, 2014)

Advantages	Disadvantages
Reduces flood risk to the structure and its contents	May be cost-prohibitive
Eliminates the need to relocate vulnerable items above the flood level during flooding	May adversely affect the structure's appearance
Often reduces flood insurance premiums	May adversely affect access to the structure
Reduces the physical, financial, and emotional strains that accompany flood events	Cannot be used in areas with high-velocity water flow unless special measures are taken
Does not require the additional land that may be needed for floodwalls or levees	Requires consideration of forces from wind and seismic hazards and possible changes to building design

(A) House before floor levels are elevated in USA (FEMA, 2014)

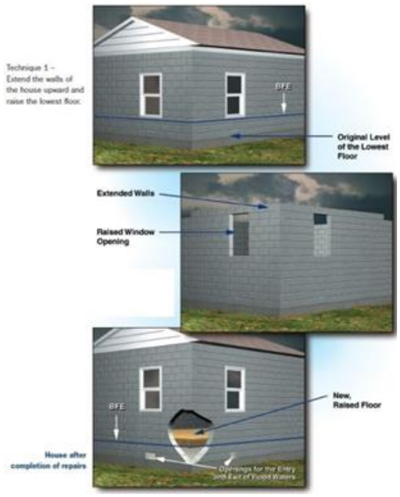
(B) House after elevation in USA (FEMA, 2014)

(C) House before floor levels are elevated in Australia

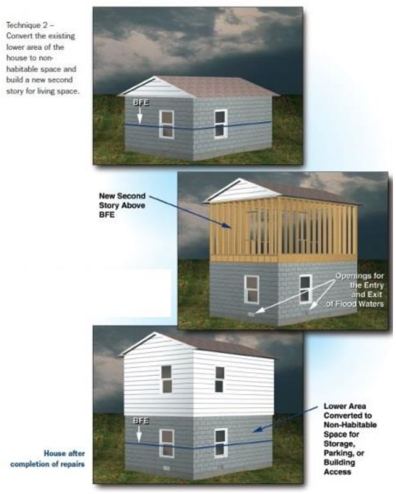
(D) House after elevation in Australia

Figure 4. Examples of elevating floor levels

(A) Technique 1: Extend the walls of the house upward and raise the lowest floor



(B) Technique 2: Change the ground floor use and build a second storey



(C) Technique 3: Elevate the whole house and build new foundation

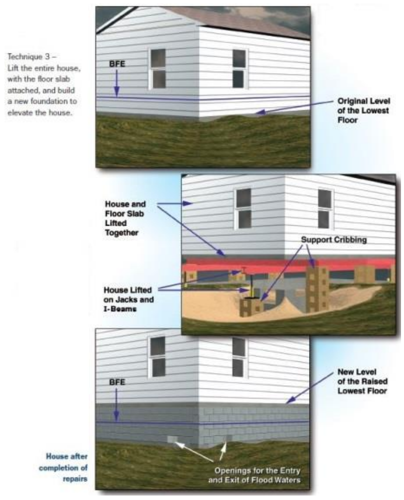


Figure 5. Techniques for elevating floor levels (FEMA, 2000)

RELOCATION

Relocation of a building is the most dependable technique in mitigation of flood risk. However, it is generally the most expensive as well (USACE, 1993). Relocation involves moving a structure to a location that is less prone to flooding or exposed to flood-related hazards such as erosion or scouring. Relocation normally involves placing the structure on a wheeled vehicle, as shown in Figure 6. The structure is then transported to a new location and set on a new foundation (FEMA, 2012). Relocation is much easier and cost effective for low-set timber frame structures. The relocation of slab-on-grade structures is more complicated and expensive. In this case there are two approaches to relocating: detaching the structure from the slab or moving the structure with the slab attached (USACE, 1990).

Relocation is most appropriate in areas where flood conditions are severe such as a high likelihood of deep flooding, or where there is high flow velocity with short warning time and a significant quantity of debris. The technical considerations for relocation include structure type, its size and condition. Light weight timber structures are easy to transport compared to heavy masonry and concrete buildings. Similarly, relocation of single storey compact size structures is far easier than for large multi-storey structures. Further, the structure should be in good condition and able to withstand the stresses imposed when the structure is lifted and relocated (FEMA, 2007). Relocation of a structure involves costs for moving the structure to its new location, purchasing and preparing a new site with utilities, the construction of new foundations, and the restoration of the old site.

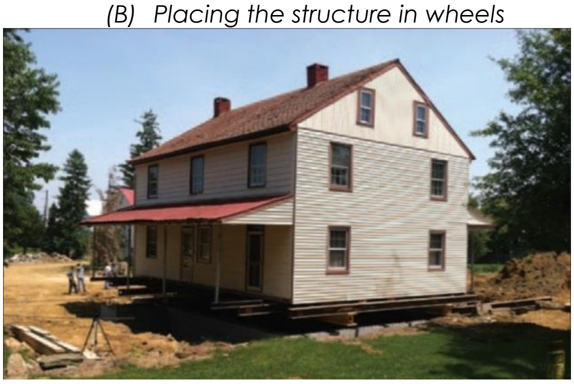
Table 3 provides some of the advantages and disadvantages of building relocation.

TABLE 3: ADVANTAGES AND DISADVANTAGES OF BUILDING RELOCATION (FEMA, 2014)

Advantages	Disadvantages
Significantly reduces flood risk to the structure and its contents	Requires procuring a new site
Can eliminate the need to purchase flood insurance or reduce the premium because the new house is no longer in the floodplain	Requires addressing disposal of the flood-prone site
Uses established techniques	May be cost-prohibitive to relocate, as well as to develop the new site with desired utilities (water, sewage, electrical, natural gas, cable, telephone etc.)
Can be initiated quickly	
Reduces the physical, financial, and emotional strains that accompany flood events	

(A) Elevating the structure

(B) Placing the structure in wheels



(C) Moving the structure to new site

(D) Placing the structure on new foundations

Figure 6. Relocating a structure to a new site (FEMA, 2014)

DRY FLOODPROOFING

In dry floodproofing the portion of a structure that is below the expected flood level is sealed to make it substantially impermeable to floodwaters. Such an outcome is achieved by using sealant systems which include wall coatings, waterproofing compounds, impervious sheeting over doors and windows and a supplementary leaf of masonry (FEMA, 2012). The expected duration of flooding is critical when deciding which sealant systems to use because seepage can increase with time making flood proofing ineffective (USACE, 1993). Preventing sewer backflow by using backwater valves is also important in making dry floodproofing effective (Kreibich et al. 2005; FEMA, 2007). Sump pumps are also used to drain out the water which may leak through small openings or exterior walls (FEMA, 2013).

The flood characteristics which can affect the success of dry floodproofing are flood depths, flow velocity, flood duration, flood borne debris and length of warning time (FEMA, 2007).

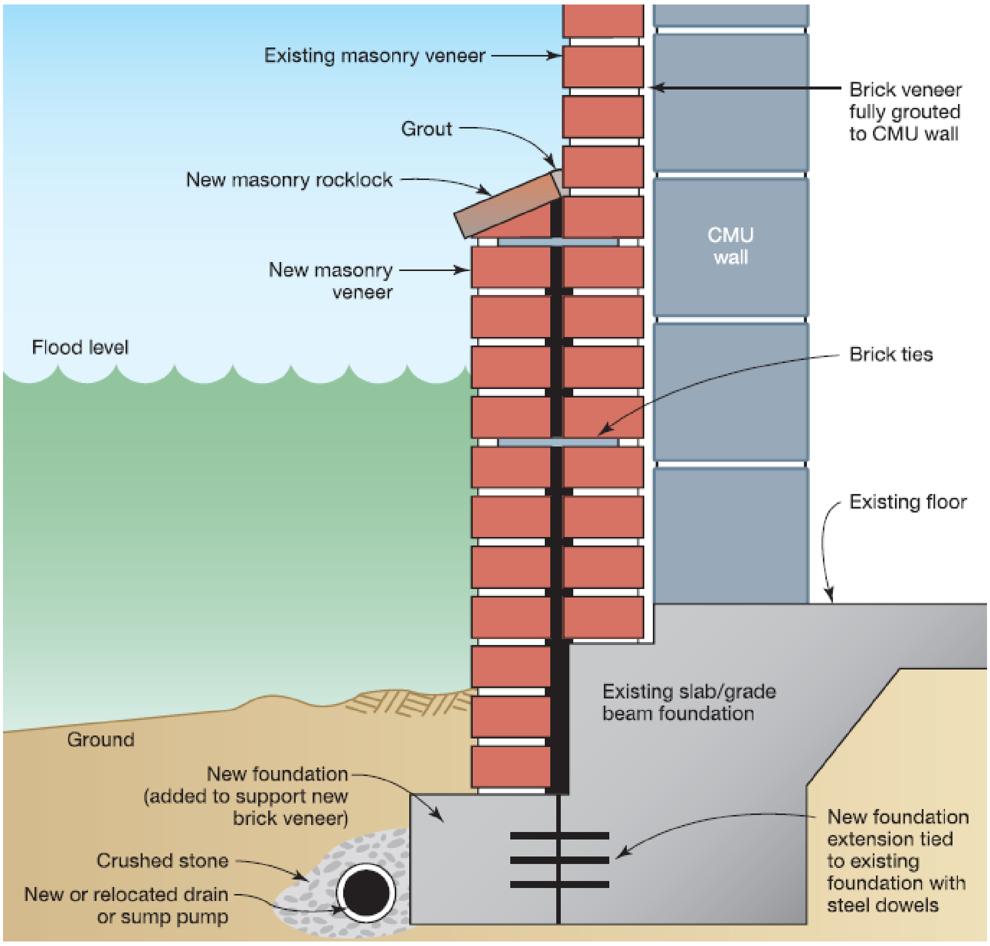
Dry floodproofing is generally not recommended in flood depths exceeding one metre based on test carried out by the US Army Corps of Engineers as the stability of the building becomes an issue over this threshold depth (USACE, 1988; Kreibich et al. 2005). Dry floodproofing is also not recommended for lightweight low-set structures or structures with a basement. These types of structure can be susceptible to significant lateral and uplift (buoyancy) forces. Dry floodproofing may also be inappropriate for light timber frame structures and structures which are not in good condition and may not be able to withstand the forces exerted by the floodwater (FEMA, 2012). Figure 7 provides some examples of dry floodproofing.

Table 4 provides some of the advantages and disadvantages of dry floodproofing.

TABLE 4: ADVANTAGES AND DISADVANTAGES OF DRY FLOODPROOFING (FEMA, 2014)

Advantages	Disadvantages
Reduces flood risk to the structure and its contents if the design flood level is not exceeded	Usually requires human intervention and adequate warning time
May be less costly than other retrofitting measures	May not provide protection if measures fail or the flood event exceeds the design parameters
Retains the structure in its present environment and may avoid significant changes in appearance	May result in more damage than flooding if design loads are exceeded or walls collapse
Reduces the physical, financial, and emotional strains that accompany flood events	Does not eliminate the need to evacuate during floods
	May adversely affect the appearance if shields are not aesthetically pleasing
	May not reduce damage to the exterior of the building

(A) Technique 1: adding extra leaf of masonry



(B) Technique 2: Shielding openings (doors and windows)

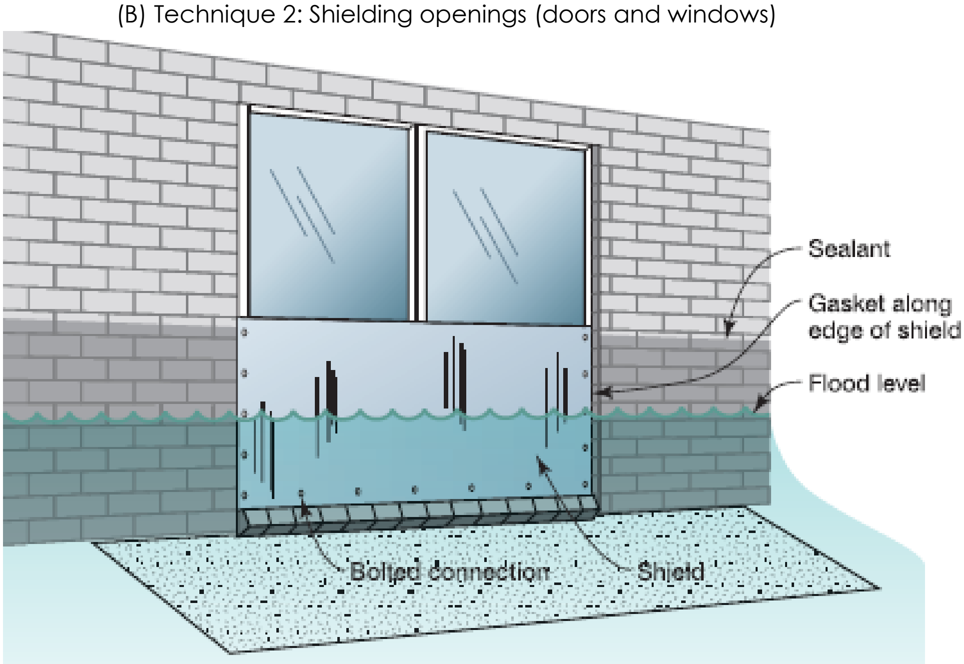


Figure 7. Techniques for dry floodproofing (FEMA, 2000)

WET FLOODPROOFING

In this measure the building is modified and floodwater is allowed to enter into the building to equalise the hydrostatic pressure on the interior and exterior of the building and thus reduces the chance of building failure as shown in Figure 8 (USACE, 1993; FEMA, 2007). With this technique, as all the building components below the flood level are wetted, all construction material and fit-outs should be water-resistant and/or can be easily cleaned following a flood. Flood resistant material is defined as any building product (material, component or system) which is capable of withstanding direct and prolonged contact with floodwaters without sustaining significant damage (FEMA, 2008c). Flood resistant materials can help reduce flood damage and facilitate cleanup to allow buildings to be restored to service as quickly as possible. As an example, wooden floor panels can easily be damaged by water, however, floor tiles are less susceptible to water damage and can reduce loss to a great extent (Kreibich and Thieken, 2008). FEMA (2008c) provides a detailed list of building materials classified as acceptable or unacceptable for wet floodproofing based on cleanability and water resistance.

Wet floodproofing involves raising utilities (heating, ventilation, and air conditioning (HVAC), electrical systems etc.) and important contents above the expected flood level, installing flood openings to equalise the hydrostatic pressure exerted by floodwaters and installing pumps to remove floodwater if the building has a basement (FEMA, 1999). A minimum of two openings should be provided on different sides of a building, should not be higher than 30cm up from the floor level and should be equipped with screens (FEMA, 2008b).

In a study conducted by Kreibich et al. 2005, wet floodproofing through adapted use (changing ground floor usage), adapted interior finishes (use of floor resistant materials) and installing utilities at higher levels has resulted in reductions of building mean damage by 46%, 53% and 36%, respectively in Germany during the 2002 floods. The damage ratio for contents was reduced by 48% due to flood adapted use and by 53% due to flood adapted interior fitting.

Wet floodproofing may not be suitable in floods with duration of more than a day as longer duration leads to damage to structural components of the building and also results in the growth of algae and mould (FEMA, 2007). The method may also be inappropriate if the building is subject to flash flooding and there is not enough warning time to move valuable items to an upper level. Also wet floodproofing can only reduce loss from floods but cannot eliminate loss as some amount of cleanup and cosmetic repair will always be necessary (USACE, 1984). Although using flood damage resistant materials can reduce the amount and severity of water damage, it does not protect buildings from other flood hazards, such as the impact of floodborne debris. Table 5 provides some of the advantages and disadvantages of this mitigation strategy. Figure 8 provides some examples of wet floodproofing.

TABLE 5: ADVANTAGES AND DISADVANTAGES OF WET FLOODPROOFING (FEMA, 2014)

Advantages	Disadvantages
Greatly reduces loads on walls and floors due to equalized hydrostatic pressure	Usually requires human intervention and adequate warning time to prepare the building and contents for flooding
Costs less than other measures	Results in a structure that is wet on the inside and may require extensive clean up
Reduces the physical, financial, and emotional strains that accompany flood events	Does not eliminate the need to evacuate during floods
	May make the structure uninhabitable for some period after flooding

(A) Installing opening on each side of the structure (FEMA, 2014)

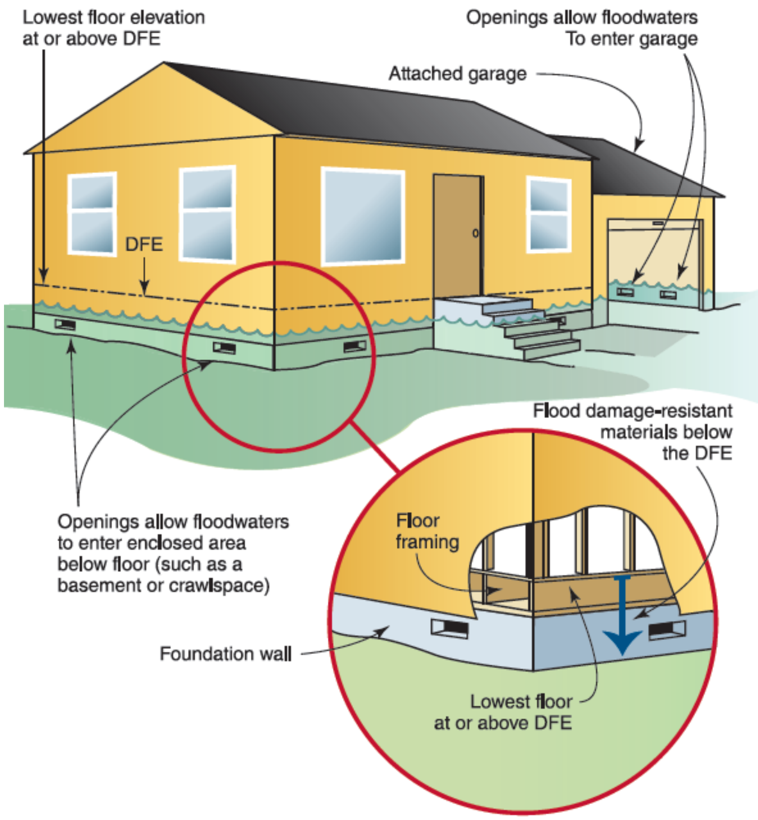
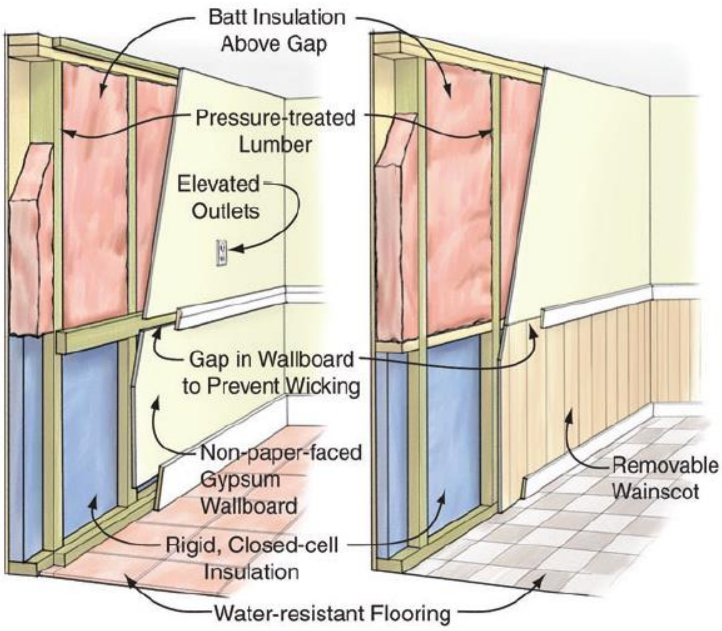


Figure 8. Techniques for wet floodproofing (FEMA, 2000)

(B) Adapted use: elevating electrical outlets, use of flood-resistant materials (FEMA, 2014)



(C) Anchoring tanks, elevating utilities, using flood-resistant materials (HNFMSC, 2006)

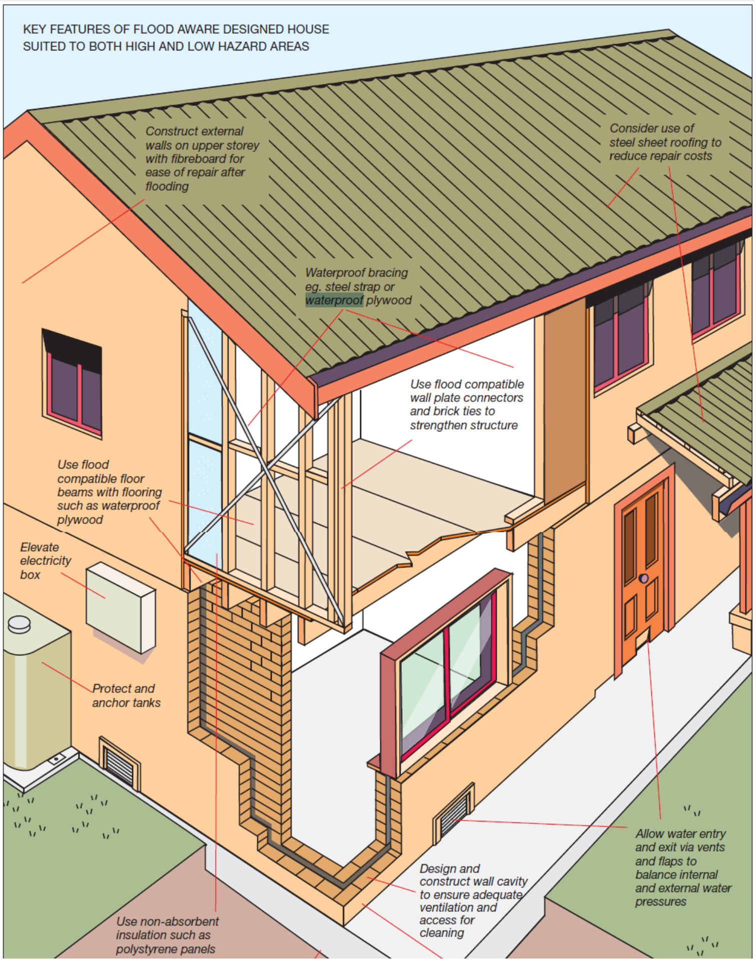


Figure 8 (Cont.). Techniques for wet floodproofing (FEMA, 2000)

FLOOD BARRIERS

Flood barriers considered here are those built around a single building and are normally placed some distance away from it to avoid any structural modifications to the building. There are two kinds of barriers: permanent and temporary.

An example of a permanent barrier is a floodwall which is quite effective because it requires little maintenance and can be easily constructed and inspected. Generally, it is made of reinforced masonry or concrete (rarely glass) and has one or more passageways that are closed by gates and require periodic maintenance. An example of a floodwall is shown in Figure 9.

There are also several types of temporary flood barriers available in the market which can be moved, stored and reused. There are a number of considerations with regard to the use of these barriers such as the need for prior warning and enough time to be set up in order to be effective (Kreibich et al. 2011). They also require periodic inspection and maintenance to address any repair required. Further, access to the building could be difficult (FEMA, 2007).

A number of vendors make temporary flood barriers that can be assembled relatively easily, moved into place, anchored, and filled with water (if required). Examples (see Figure 10) of some of the flood barrier options presented by Bluemont Pty Ltd, 2015 are:

- Sandbags: This is a traditionally less expensive way to construct a barrier up to 1m high in front of a building and its openings. However, it requires considerable time and effort to set up. As an alternative to the traditional sandbag, jute sack and cotton liner bags are also available which can be simply laid as traditional sandbags and when submerged in water these bags inflate within a few minutes through absorption.
- Tubes: These normally consist of two flexible tubes laid side by side and joined to form a twin element with high stability. They can be ready quite quickly, generally in less than 15 minutes, and are available in heights up to 1.3m and up to 20m length units. These tubes can be joined to create any length required.
- Fence: This fence system consists of two boards in compact flat packs which are lifted into place after transportation to the site and the system is stabilised by water pressure. These fences can be used in water depth up to 2.4m.
- Flexible barriers: These barriers are able to dam or redirect flowing water up to 1m high and can be set up very quickly on almost all surfaces. The rapid assembly of these barriers considerably reduces the extent of damage caused by flash flooding.
- Box wall: A freestanding flood barrier for use on smooth surfaces. These can be attached and placed next to each other to build a 0.5m high wall around a building. Its flexible coupling also makes it possible to create curves in the wall. After use, the barriers can easily be detached, cleaned and stacked.
- Box barrier: An effective temporary flood barrier (0.5m high) that can be aligned easily and rapidly. After positioning, the box is often filled with water or sand. No additional equipment is required for the installation

except for a simple pump. Removal of the system is also fast and does not leave any debris after removal.

Flood barriers are generally restricted to a height of 2m because of their stability issues, cost and visual concerns (USACE, 1993); however, most barriers are limited to about 0.5m to 0.8m. In a study in Germany, the mean damage ratio was reduced by 29% for the cases where water barriers were available during the 2002 floods (Kreibich et al. 2005).

Table 6 provides some of the advantages and disadvantages of using flood barriers.

TABLE 6: ADVANTAGES AND DISADVANTAGES OF FLOOD BARRIERS (FEMA, 2014)

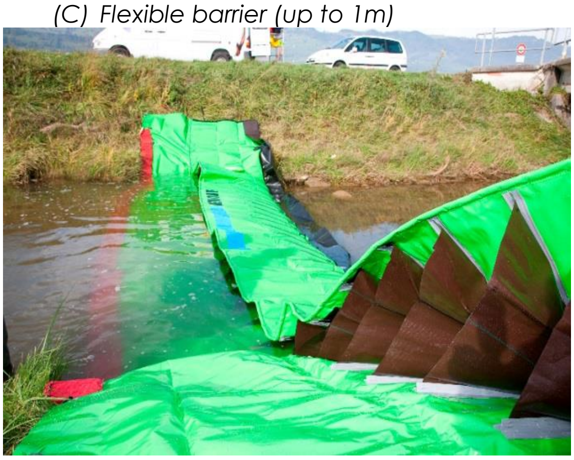
Advantages	**Disadvantages**
Protects the area around the structure from inundation without significant changes to the structure	In most cases only applicable to low inundation
Eliminates pressure from floodwaters that would cause structural damage to the home	May fail or be overtopped by large floods or floods of long duration
Allows the structure to be occupied during construction	Requires interior drainage and periodic maintenance
Reduces flood risk to the structure and its contents	May not reduce flood insurance premiums
Reduces the physical, financial, and emotional strains that accompany flood events.	May restrict access to structure
	May require warning and human intervention for closures

Figure 9. An example of a floodwall (FEMA, 2013)

(A) Sand bags (up to 1m)

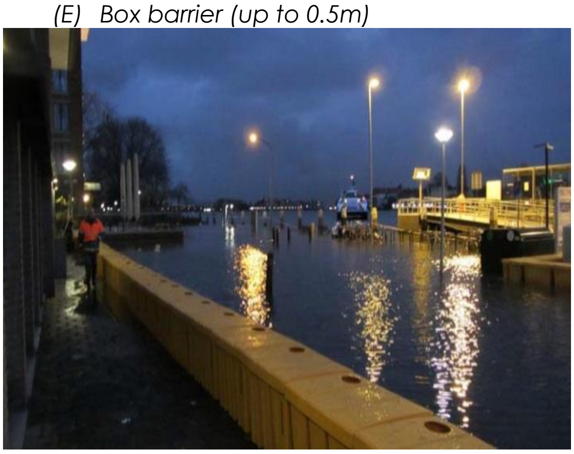
(B) Tubes (up to 1.3m)

(C) Flexible barrier (up to 1m)



(D) Boxwall (up to 0.5m)

(E) Box barrier (up to 0.5m)



(F) Fence (up to 2.4m)

Figure 10. Examples of flood barriers (Bluemont, 2015)

DECISION MAKING PROCESS

The increasing trend of flood damage to residential buildings can only be mitigated through better flood risk management by government authorities and also by improvements and mitigation efforts adopted by private households (Kreibich et al. 2010; Productivity Commission, 2014). Previous flood experience of people and fear of flood damage can also be significant motivating factors to investigate what measures can be taken to reduce flood loss risk (Siegrist and Gutscher, 2008). Financial incentives provided by government or insurers could also provide a motivation for property owner to invest in mitigation measures (Kreibich et al. 2011). Moreover, people tend to take actions only if they are informed about the effectiveness of the measures and the economic and social benefits resulting from those measures (Grothmann and Reusswig, 2006). Therefore, this project will develop an evidence base to facilitate government and private property owners to make informed decisions to carry out mitigation measures which suit their situation and circumstances.

Selecting the best mitigation option for a given situation should be based on a number of factors including flood and catchment characteristics, building characteristics, local building standard or regulations and a comprehensive benefit cost analysis (see Table 7).

Flood characteristics such as flood depth influence the choice of mitigation measure. In the case of dry floodproofing the water level difference between inside and outside the structure is quite critical and thus restricts the options for flood depths of more than a metre. For higher flood depths the option of flood barriers becomes impractical. As higher flood velocity exerts more hydrodynamic forces to the structure and may cause erosion and scouring, any mitigation option needs to take into account these extra forces. Generally higher flow velocities restrict the use of dry/wet floodproofing and flood barriers (FEMA, 2007).

Building characteristics such as construction material are important considerations as they influence the type of mitigation that is considered appropriate e.g. dry floodproofing may not be appropriate for light timber frame construction as it is more difficult to achieve water tightness. Brick veneer or solid masonry may not be appropriate for elevation or relocation as special heavy lifting processes would be required (FEMA, 2007). Building condition would influence the level of work required to carry out any mitigation option. Building foundation type also influences the selection of an appropriate mitigation option e.g. slab-on-grade could be difficult to elevate or relocate, low-set buildings may not be dry floodproofed since the floors are not water tight and flotation may also occur. Multi-storey structures are harder to elevate and relocate, even if they are made of light timber frame.

Technical and financial assistance may be available from Federal, State, or local governments to help property owners regarding the retrofit of their building. Also property owners should consult local authorities to ensure the mitigation measures will comply with local building standards.

A preliminary analysis was conducted by FEMA (2014) to exclude the combinations which are considered to be impractical or invalid. Table 8 presents a matrix of available mitigation options along with flood and building characteristics. It is believed that options like flood barriers will not be suitable in high velocity and large flood depths due to the design limitations of these barriers. Similarly dry floodproofing will also be impractical in situations with high flood depths and even in moderate flow velocities. Furthermore these may also be unsuitable for buildings with basements, poorly maintained low quality buildings, or buildings made of light timber frame which may not sustain the pressure exerted by flood water.

Traditionally, without any detailed analysis, the most common way to reduce flood risk was to raise the floor level above the flood hazard (FEMA, 2007). However, the aim of this project is to conduct a comprehensive analysis of options for different scenarios combining the above mentioned factors and evaluating monetary benefits of each option through a CBA. The result would be a clear understanding of cost and benefits involved in taking any mitigation measures. This type of evidence base will encourage governments and individuals to take responsibility and make informed decisions to reduce the flood risk in accordance to the National Strategy for Disaster Resilience (NSDR, 2011).

TABLE 7: FACTORS INVLOVED IN DECION MAKING PROCESS

Hazard characteristics	Building characteristics	Government rules	Decision
Flood depth	Construction material	Local regulations/standards	Available options
Flood velocity	Building condition	Technical assistance	Benefit/Cost assessment
	Foundation type	Financial assistance	Building approvals
	Number of storeys		

TABLE 8: FLOOD PROOFING MATRIX (FEMA, 2014)

Flood Proofing Matrix		Flood Mitigation Strategies						
		Elevation on walls	**Elevation on piers**	**Elevation on columns**	**Relocation**	**Flood barriers**	**Dry flood proofing**	**Wet flood proofing**
Flooding characteristics	**Flood depth**							
	Shallow							
	Moderate						N/A	
	Deep					N/A	N/A	
	Flow velocity							
	Slow							
	Moderate						N/A	N/A
	Fast	N/A				N/A	N/A	N/A
Building characteristics	**Building Foundation**							
	Slab-on-Grade							
	Low-set							
	Basement		N/A	N/A			N/A	
	Building Material							
	Masonry/ Concrete							
	Timber						N/A	N/A
	Number of storeys							
	One/Two							
	Three or more	N/A	N/A	N/A	N/A			
	Building Condition							
	Excellent to Good							
	Fair to Poor						N/A	N/A

DISCUSSION

The economic losses due to floods have been increasing during the last decades due to vulnerable construction types (such as slab-on-grade houses) and because of rapid urban development in floodplains which increase exposure to flooding. The increase in loss emphasises the need to improve flood risk management and to reduce future flood losses. These need to be built upon a sound analysis of flood hazard, potential losses and the effectiveness of different mitigation measures (Kreibich and Thieken, 2008).

Flood risk management broadly consists of flood risk assessment and risk mitigation (Meyer et al. 2009). The former aims to establish a risk profile in a catchment by assessing flood hazard, exposed elements at risk and the vulnerability of those elements (Smith, 1981; Penning-Rowsell et al. 2005). The latter aims to address high risk areas identified in the risk assessment studies and to alleviate this risk by proposing, evaluating, selecting and executing mitigation actions.

Flood risk management not only includes the measures taken by government but also includes mitigation measures adopted by private property owners to reduce the potential losses. These measures include elevating structures above the expected flood level, relocating the structure outside the floodplain, dry floodproofing to make the structure water tight, wet floodproofing by using water-resistant materials and installing flood barriers to keep water away from the building. These efforts have a significant potential to reduce flood damage to buildings and contents particularly in low to moderate flood levels. Selection and implementation of any of these strategies would require comprehensive analysis of characteristics of flood, local building standards and a cost benefit analysis to evaluate the optimum strategy.

Although most of these measures are well known, they have not been broadly implemented possibly because good cost-benefit studies are lacking (Bouwer et al. 2011; Bubeck et al. 2012). Some studies that underpin the usefulness of these measures have been conducted by Smith, 1981; USACE, 2001; Kreibich et al. 2005; Botzen et al. 2009 and Kreibich et al. 2011. To facilitate the implementation of mitigation actions more studies should be conducted which inform governments and property owners on the possible actions, their effectiveness and long term benefits. Further, incentives given by government and the insurance industry could also motivate private households to implement these measures.

This BNHCRC project aims to conduct a comprehensive analysis of mitigation options and evaluate each of them through CBA for use in Australian conditions. The result would be a clear understanding of cost and benefits involved in implementing any of these mitigation measures. This evidence base will facilitate and encourage governments and property owners to make informed and optimal decisions to reduce flood risk.

NEXT STEPS

The literature review presented in this report draws together a large body of literature about flood mitigation strategies and provides a useful perspective for the Australian environment. The strategies presented here have relevance to the Australian context and therefore the mitigation options provided in Table 8 will be considered a starting point for the analysis to follow.

Further research in this project will explore the susceptibility of common building materials to water in Australia through laboratory tests. The building schema which has been developed within this project will facilitate the selection of Australian building types for which specific strategies will need to be developed. Moreover the costing of different mitigation strategies will be carried out by quantity surveyors to ascertain costs based on flood and building characteristics in Australia. Optimum strategies will then be assessed through CBA.

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