FINAL PROJECT REPORT
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COST-EFFECTIVE MITIGATION STRATEGY DEVELOPMENT FOR FLOOD PRONE BUILDINGS

Final project report

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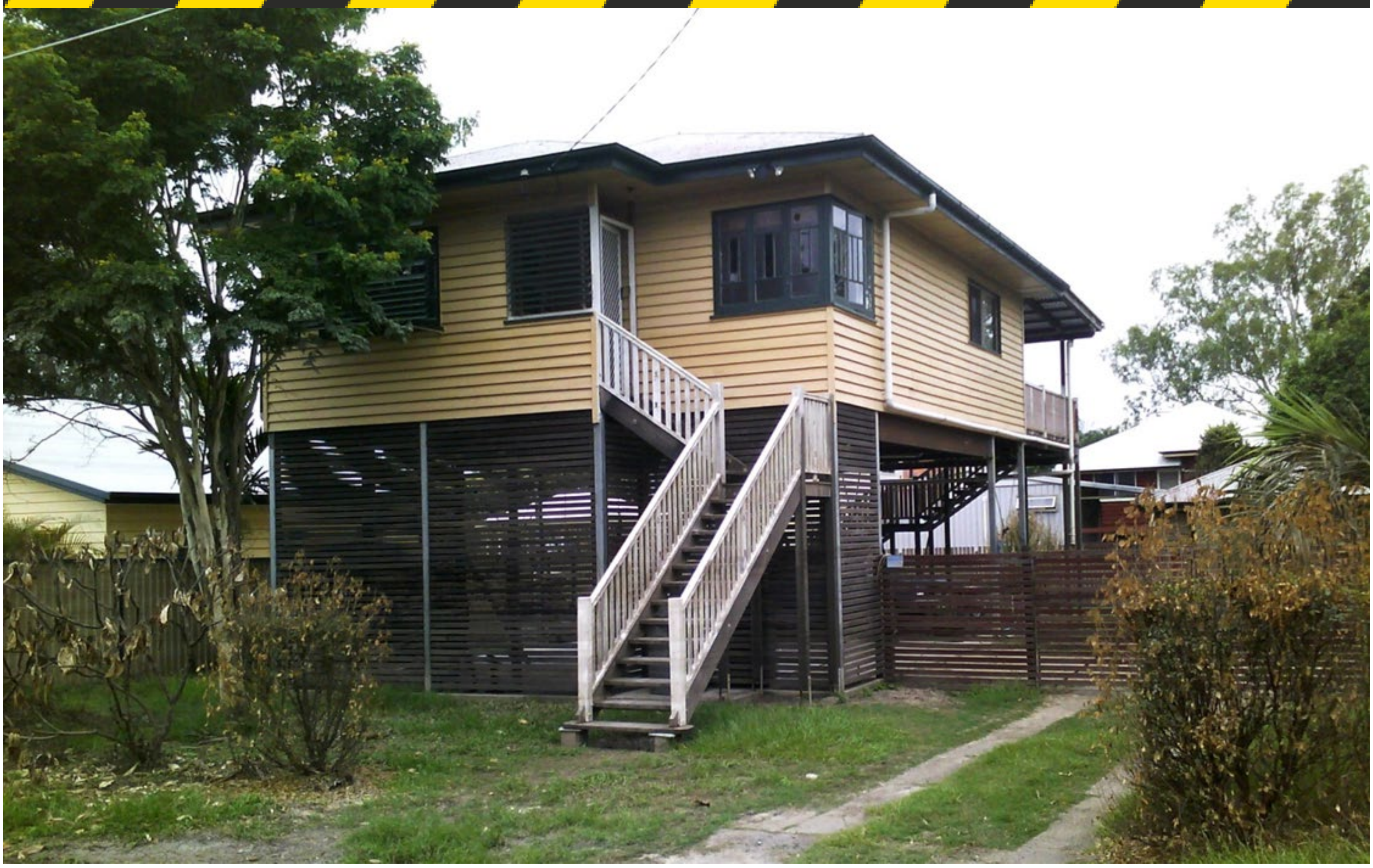

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Cover: Flood mitigation strategy: elevating floor level. Source: Geoscience Australia

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ABBREVIATIONS

AAL	Average Annual Loss
ABCB	Australian Building Codes Board
AIDR	Australian Institute for Disaster Reduction
ARI	Average Recurrence Interval
BCR	Benefit versus Cost Ratio
CRC	Bushfire and Natural Hazards Cooperative Research Centre
DRR	Disaster Risk Reduction
FEMA	Federal Emergency Management Agency
FMA	Floodplain Management Australia
HVAC	Heating Ventilation and Air Conditioning
HDF	High Density Fibreboard
LCC	Launceston City Council
NEXIS	National Exposure Information System
NFRAG	National Flood Risk Advisory Group
OSB	Oriented Strand Board
PMF	Probable Maximum Flood
RHS	Rectangular Hollow Section
USACE	United States Army Corps of Engineers

ACKNOWLEDGMENTS

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- City of Launceston
- Launceston Flood Authority
- Tasmanian Department of Premier and Cabinet
- Northern Midlands Council
- Tasmanian State Emergency Service
- National Flood Risk Advisory Group (NFRAG)
- Floodplain Management Australia (FMA)
- Australian Institute for Disaster Resilience (AIDR)
- Insurance Australia Group
- Insurance Council of Australia
- Wagga Wagga City Council
- Tweed Shire Council
- Brisbane City Council
- Bundaberg Regional Council
- BMT WBM
- University of Western Australia
- City of Sydney
- NSW State Emergency Service
- Suncorp Insurance

EXECUTIVE SUMMARY

The motivation for this project arises from the experience and observations made during the 2011 and 2013 floods in Australia, which caused widespread devastation in Queensland. Considerable costs were sustained by all levels of government and property owners to effect damage repair and enable community recovery.

A fundamental reason for this damage was inappropriate development in floodplains and a legacy of high risk building stock in flood prone areas. While the vulnerability and associated flood risk for newer construction is being addressed (moderated) by new standards (ABCB, 2012), building controls and land use planning, the vulnerability associated with existing building stock remains. This vulnerability contributes disproportionally to overall flood risk in many Australian catchments.

The Bushfire and Natural Hazards Collaborative Research Centre (CRC) project entitled *Cost-effective mitigation strategy development for flood prone buildings* addresses this issue and is targeted at assessing mitigation strategies to reduce the vulnerability of existing residential building stock in Australian floodplains. The project addresses the need for an evidence base to inform decision making on the mitigation of the flood risk posed by the most vulnerable Australian houses and complements parallel CRC projects for earthquake and severe wind.

The project has developed a building classification schema to categorise Australian residential buildings into a range of typical storey types. Mitigation strategies developed nationally and internationally have been reviewed. A floodproofing matrix has been developed to assess appropriate strategies for the selected storey types. All appropriate strategies have been costed for the selected storey types through the engagement of quantity surveying specialists. Vulnerability curves have been developed featuring reduced losses achieved through appropriate mitigation strategies for the five selected storey types.

Furthermore, selected building materials/systems have been tested to ascertain their resilience to floodwater exposure. These tests were aimed at addressing knowledge gaps in the areas of strength and durability of building materials during immersion.

A research utilisation project with NFRAG, AIDR and FMA as key stakeholders commenced in 2018. The project has developed generalised vulnerability functions for use by floodplain managers who may not have detailed exposure information.

In concluding the project, cost benefit analyses of mitigation options were conducted at three levels of resolution. These have added to cost versus benefit work already completed by the project team for Launceston as a utilisation project. The results are 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.

This report describes the research methods, project activities, outcomes and their potential for utilisation.

END-USER PROJECT IMPACT STATEMENT

Leesa Carson, *Community Safety Branch, Geoscience Australia, ACT*

Floods historically have, and continue to, cause widespread damage and disruption to Australian communities. This project has sought to provide an evidence base to assist governments and householders in making informed decisions on reducing flood risk through retrofit of existing houses to reduce flood vulnerability.

During the past year the project finalised its scheduled tasks building on the achievements of the previous years. The last key deliverable completed was the cost versus benefit analysis. This activity drew together the previous project deliverables and assessed the cost-effectiveness of building level mitigation options for residential buildings subjected to three different catchment behaviours. This has complemented earlier work examining community level mitigation in Launceston, and building level mitigation in Newstead. The evidence base provides very useful information on the most cost-effective mitigation options for five different residential building types.

The utilisation project focused on the development of a suite of generalised vulnerability functions has also been completed. The generalised curves are intended for use by floodplain managers or others with an interest in flood impact and risk who may not have detailed exposure information. The suite of generalised curves have the potential for broad utilisation, including possible application in a national scale flood impact forecasting capability.

Key project stakeholders include the CRC, the National Flood Risk Advisory Group (NFRAG), the Australian Institute for Disaster Resilience (AIDR) and Floodplain Management Australia (FMA). Engagement in the final years of the project has been hampered by the ongoing COVID-19 pandemic, with a one day online workshop the key stakeholder activity in March this year. The workshop was productive and was a good mechanism for feedback and suggestions to the project team.

Aside from the workshop and standard reporting to the CRC, an oral presentation at the FMA conference in May and a poster presentation at the upcoming AFAC21 in Sydney have been the main mechanisms for recent dissemination.

INTRODUCTION

Globally, floods cause widespread impacts with loss of life and damage to 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 cause of this level of damage and the key factor contributing to flood risk, in general, is the presence of vulnerable buildings constructed within floodplains due to ineffective land use planning.

Retrospective analysis show large benefits from disaster risk reduction (DRR) in the contexts of many developed and developing countries. A study conducted by the U.S. Federal Emergency Management Agency (FEMA) found an overall benefit-cost ratio of four suggesting that DRR can be highly effective in future loss reduction (MMC, 2005). However, in spite of potentially high returns, there is limited research in Australia on assessing benefits of different mitigation strategies with consequential reduced investment made in loss reduction measures by individuals and governments. This is true not only at an individual level but also at national and international levels. According to an estimate, international donor agencies allocate 98% of their disaster management funds for relief and reconstruction activities and just 2% is allocated to reduce future losses (Mechler, 2011).

The Bushfire and Natural Hazards Collaborative Research Centre project entitled *Cost-effective mitigation strategy development for flood prone buildings* is examining the opportunities for reducing the vulnerability of Australian residential buildings to riverine floods. It addresses 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 CRC projects for earthquake and severe wind.

This project investigates methods for the upgrading of the existing residential building stock in floodplains to increase their resilience in future flood events. It aims to identify economically optimal upgrading solutions so the finite resources available can be best used to minimise losses, decrease human suffering, improve safety and ensure amenity for communities.

This report describes the research methods, project activities, outcomes and their potential for utilisation.

BACKGROUND

In Australia, floods cause more damage on an average annual cost basis than any other natural hazard. Figure 1 shows the Average Annual Losses (AAL) by disaster type in Australia from 2007 to 2016 (DAE, 2017). The fundamental cause of this level of damage and the key factor contributing to flood risk, in general, is the presence of vulnerable buildings constructed within floodplains due to ineffective land use planning.

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).

Community level mitigation options such as levees, dams and retention basins have been implemented by governments in many catchments in Australia but there always remains a residual risk. Recently there has been a growing body of research both nationally and internationally that measures the potential of reducing flood risk by implementing property level flood mitigation options (Kreibich et al. 2011; Thieken et al. 2016).

The Bushfire and Natural Hazards Collaborative Research Centre project entitled *Cost-effective mitigation strategy development for flood prone buildings* (CRC, 2021a) is examining the opportunities for reducing the vulnerability of Australian residential buildings to riverine floods. It addresses 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 CRC projects for earthquake and severe wind.

This project investigates methods for the upgrading of the existing residential building stock in floodplains to increase their resilience in future flood events. It aims to identify economically optimal upgrading solutions so the finite resources available can be best used to minimise losses, decrease human suffering, improve safety and ensure amenity for communities.

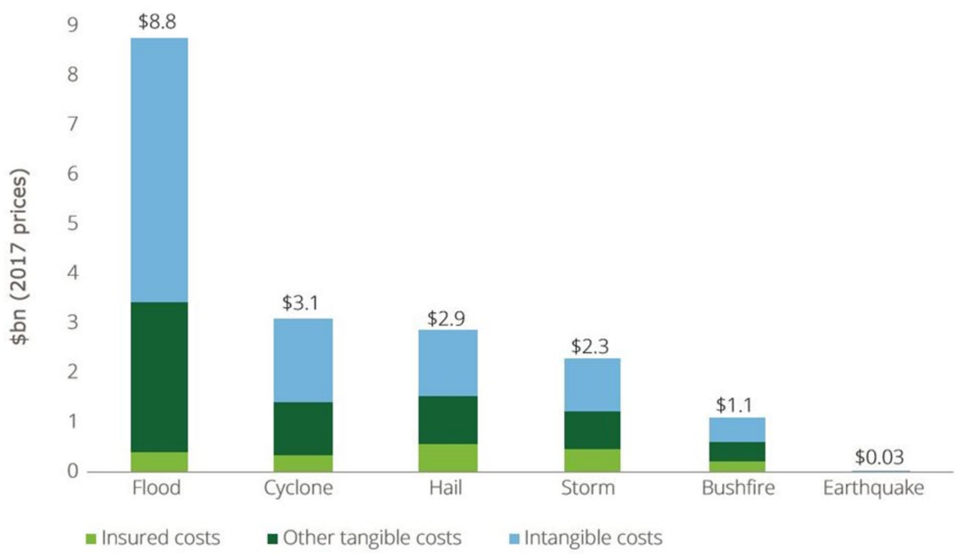

FIGURE 1: AVERAGE ANNUAL LOSSES BY DISASTER TYPE IN AUSTRALIA FROM 2007 TO 2016 (DAE, 2017)

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 the losses arising from past or future flood 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 better understand the potential risk to their properties due to floods and to make decisions on undertaking mitigation measures to reduce risk and (possibly) their insurance premiums (Meyer et al. 2012).

RESEARCH APPROACH

Information on the vulnerability of buildings and factors affecting vulnerability is fundamental to evaluating mitigation strategies to reduce future losses. Therefore, this CRC project systematically developed information about residential building types in Australia, their vulnerability and possible mitigation measures to reduce their vulnerability.

The research approach and associated milestones broadly align with the activities mentioned in the above paragraph:

- a building classification schema has been developed to categorise Australian residential buildings into a finite set of typical building types.
- a literature review of flood mitigation strategies applied internationally has been conducted.
- an experimental program has been undertaken to examine the impact of immersion in water (simulating slow flood water rise and fall) on structural and other building components.
- each mitigation strategy has been evaluated and costed through the engagement of professional quantity surveyors.
- cost benefit analyses were conducted to determine optimum retrofit strategies for selected building types applicable to a range of catchment behaviours.

Each of these research activities is described further in the following sections of this report.

Other research associated with the project includes a virtual retrofit of properties in Launceston aimed at quantifying the benefit versus cost of a variety of mitigation options.

KEY MILESTONES

There were five key milestones associated with this project. A summary of the project activities is provided below:

BUILDING CLASSIFICATION SCHEMA

Following a literature review a new schema was proposed in this project to categorise Australian residential building stock into a limited number of typical storey types. It was a fundamental shift from describing the complete building as an entity to one that focuses on sub-components. The proposed schema divided each building into the sub-elements of foundations, bottom floor, upper floors (if any) and roof to describe its vulnerability (see Figure 2).

Through this approach it was made possible to assess the vulnerability of structures with different usage and/or construction materials used in different floors, and also to assess the vulnerability of tall structures with basements where only basements and/or bottom floors are expected to be inundated (Maqsood et al. 2015a). The schema classified each storey type based on six attributes: construction period, fit-out quality, storey height, bottom floor, internal wall material and external wall material. The full schema and appropriate selections (dark cells) is presented in Table 1 (pre-1960) and Table 2 (post-1960).

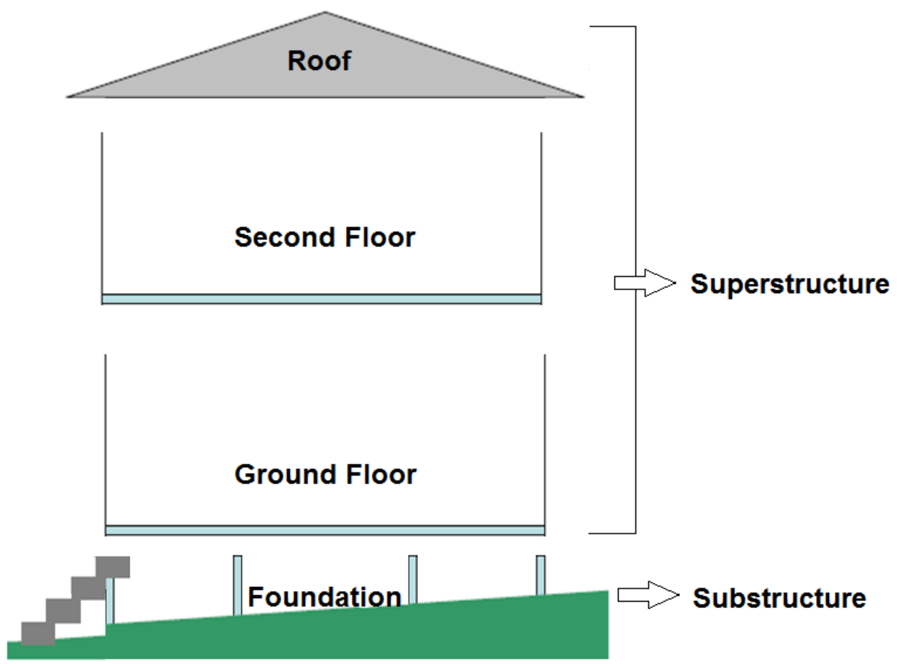

FIGURE 2: BUILDING STRUCTURE DIVIDED INTO MAIN COMPONENTS

TABLE 1: SCHEMA (PRE-1960). DARK SHADED CELLS REPRESENT POSSIBLE COMBINATIONS OF ATTRIBUTES

Construction period	Fit-out quality	Storey Height (m)	Floor system	Internal wall material	External wall material		
					Brick veneer	Weatherboard/ Timber/Fibro	Solid brick/Cavity brick/Concrete
Pre-1960	Standard	2.7	Slab-on-grade	Masonry			
				Plasterboard /Hardboard			
				Timber			
			Raised: Timber	Masonry			
				Plasterboard /Hardboard			
				Timber			
		3.0	Slab-on-grade	Masonry			
				Plasterboard /Hardboard			
				Timber			
			Raised: Timber	Masonry			
				Plasterboard /Hardboard			
				Timber			
	Low	2.7	Slab-on-grade	Masonry			
				Plasterboard /Hardboard			
				Timber			
			Raised: Timber	Masonry			
				Plasterboard /Hardboard			
				Timber			
		3.0	Slab-on-grade	Masonry			
				Plasterboard /Hardboard			
				Timber			
			Raised: Timber	Masonry			
				Plasterboard /Hardboard			
				Timber			

TABLE 2: SCHEMA (POST-1960). DARK SHADED CELLS REPRESENT POSSIBLE COMBINATIONS OF ATTRIBUTES

Construction period	Fit-out quality	Storey Height (m)	Floor system	Internal wall material	External wall material		
					Brick veneer	Weatherboard/ Timber/Fibro	Solid brick/Cavity brick/Concrete
Post-1960	Standard	2.4	Slab-on-grade	Masonry			
				Plasterboard /Hardboard			
			Raised: Timber	Masonry			
				Plasterboard /Hardboard			
			Raised: Chipboard	Masonry			
				Plasterboard /Hardboard			
		2.7	Slab-on-grade	Masonry			
				Plasterboard /Hardboard			
			Raised: Timber	Masonry			
				Plasterboard /Hardboard			
			Raised: Chipboard	Masonry			
				Plasterboard /Hardboard			
	Low	2.4	Slab-on-grade	Masonry			
				Plasterboard /Hardboard			
			Raised: Timber	Masonry			
				Plasterboard /Hardboard			
			Raised: Chipboard	Masonry			
				Plasterboard /Hardboard			
		2.7	Slab-on-grade	Masonry			
				Plasterboard /Hardboard			
			Raised: Timber	Masonry			
				Plasterboard /Hardboard			
			Raised: Chipboard	Masonry			
				Plasterboard /Hardboard			

LITERATURE REVIEW OF FLOOD MITIGATION STRATEGIES

The next task completed in this project was a literature review of mitigation strategies developed nationally and internationally. The review aimed to evaluate the strategies that would suit Australian building types and typical catchment behaviours. The review categorised mitigation strategies into five categories: elevation, relocation, dry floodproofing, wet floodproofing and flood barriers. These categories are described in the following sections with full reporting on the milestone provided by Maqsood et al. (2015b).

Elevation

Elevation of a structure is one of the most common mitigation strategies where the aim is to raise the lowest habitable floor of a building above the expected level of flooding. This can be achieved 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 3.

FIGURE 3: AUSTRALIAN EXAMPLE OF MITIGATION THROUGH ELEVATION

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 more expensive when other factors are included such as slab-on-grade construction, walls of masonry or concrete or application to a multi-storey building (USACE, 1993). Elevation is one of the strategies which currently can result in incentives from the insurance industry in the form of reductions in annual premiums for flood insurance (Bartzis, 2013).

Relocation

Relocation of a building is a dependable flood mitigation technique. 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. Relocation normally involves placing the structure on a wheeled vehicle, as shown in Figure 4. 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.

FIGURE 4: RELOCATION (FEMA, 2012)

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. Technical considerations for relocation include the structure type, size and condition. Light weight timber structures are easy to transport compared to heavy masonry and concrete buildings. Similarly, the relocation of single storey compact size structures is far easier than for large multi-storey structures.

Dry floodproofing

Dry floodproofing essentially attempts to keep floodwaters out of the house. The portion of a structure that is below the expected flood level is sealed to make it substantially impermeable to floodwaters. This 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).

Dry floodproofing is generally not recommended in flood depths exceeding one metre based on tests 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 that are not in good condition and may not be able to withstand the forces exerted by the floodwater (FEMA, 2012).

Wet floodproofing

In this measure floodwater is allowed to enter the building to equalise the hydrostatic pressure on the interior and exterior of the building, thus reducing the chance of building failure due to a pressure differential on components. 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 materials can help reduce flood damage and facilitate cleanup to allow buildings to be restored to service as quickly as possible. FEMA (2008) 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. Wet floodproofing may not be suitable in floods with duration of more than a day as longer duration can lead to damage to structural components of the building and can also result in the growth of algae and mould (FEMA, 2007). 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.

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 and has one or more passageways that are closed by gates. An example of a floodwall is shown in Figure 5.

FIGURE 5: AN EXAMPLE OF A FLOODWALL (FEMA, 2013)

There are also several types of temporary flood barriers available on 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 and moved into place. Some of the temporary flood barrier options are presented below and shown in Figure 6.

Sandbags: This is a traditional and 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.

PVC tubes: These consist of two flexible tubes laid side by side and joined permanently to form a twin element with high stability. They can be made ready quite quickly, generally in less than 15 minutes, and are available in 1m height and 10m length units.

Metal boards/fence: This fence system consists of two boards in compact flat packs that are lifted into place after transportation to the site and the system is stabilised by water pressure.

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.

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.

Box barrier: An effective temporary flood barrier (0.5m high) that can be aligned easily and rapidly. After positioning, the box can be filled with water to hold it in place.

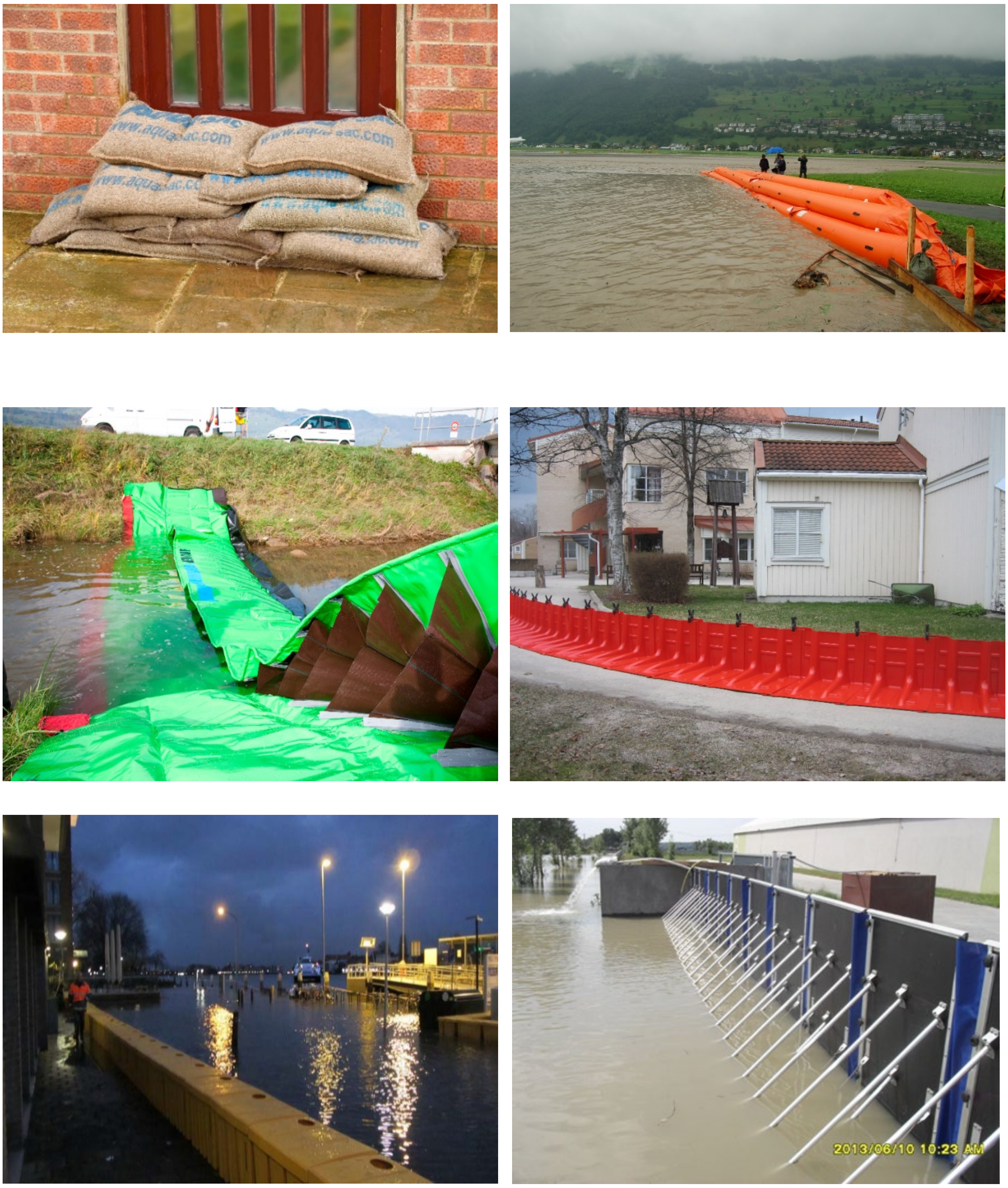

FIGURE 6: EXAMPLES OF TEMPORARY FLOOD BARRIERS (BLUEMONT, 2021)

TESTING OF SIMULATED FLOOD EFFECT ON THE STRENGTH OF SELECTED BUILDING COMPONENTS

In this project the strength and durability implications of the immersion of key structural elements and building components in conditions of slow water rise were examined to ascertain deterioration due to wetting and subsequent drying. The objective of the testing was to identify whether the selected components remain serviceable following inundation and subsequent drying or whether replacement was required. The Cyclone Testing Station at James Cook University in Townsville, Queensland, was engaged to conduct the experimental tests. These tests aimed to address knowledge gaps in the areas of strength and durability implications of selected components of a typical brick veneer slabon-grade house due to immersion.

The experimental program examined the bond strength of floor and wall ceramic tiles to their substrate with the objective of determining the necessity or otherwise of replacing all tiles following inundation. The experiments also explored the racking strength of Oriented Strand Board (OSB) and High Density Fibreboard (HDF) sheet wall bracing, and the bending and shear strength of engineered timber joists. The three test series are described further in the sections below with full reporting available in Maqsood et al. (2017a).

Test Type 1 (Floor and Wall Tiles)

Test Type 1 was designed to test the bond of ceramic floor and wall tiles to their substrate along with wet proofing treatments. Three samples were to have the enclosure finished as for a bathroom and three samples were to have the enclosure finished as for a shower.

Two bathroom and two shower simulated samples were placed in a water tank and the water level was raised to 600 mm above the floor tiles for four days. Figure 7 shows two samples in the tank with water. Subsequently the water was drained out, the samples were removed from the tank and were placed in a ventilated sheltered drying area for a duration of six weeks.

FIGURE 7: BATHROOM SAMPLES IN WATER TANK DURING FLOOD SIMULATION

For each sample a total of seven tile pull-out tests were performed, three on floor tiles and four on wall tiles (two on the end wall and two on the left side wall). Steel RHS sections were bonded to the surface of the tiles to be tested in order to provide an anchoring point to perform the testing (Figure 8).

FIGURE 8: LOCATION OF TILES TO BE TESTED AND ANHOR POINTS BONDED ON TILES

Visual inspection of the specimens by an insurance loss assessor indicated that the depth of water the specimens had been submersed in was evident with discolouration of the tiles and sheet lining. No evidence of delamination of the adhesive of tiles causing lifting or popping was observed (Van Gender, 2017). Therefore, based on the observations of the team and the insurance loss assessor replacement of tiles after flooding was not considered to be necessary by this research.

The pull out tests on the tiles indicated that flooding did not have any adverse impact on the bond strength of the ceramic floor and wall tiles to their substrate.

Test Type 2 (OSB and HDF Wall Sheet Bracing)

Test Type 2 was designed to test the structural adequacy of structural wall sheet bracing following inundation and subsequent drying. Two types of wall sheet bracing were tested for racking strength: oriented strand board (OSB) and high-density fibreboard (HDF).

A test programme to evaluate the racking strength of the two types of wall sheet bracing was conducted. Ten specimens were constructed for each bracing material. Five of them were tested in a dry condition without being flooded as control specimens and the other five were tested after a wetting and drying cycle. Five OSB samples and five HDF samples were placed in an immersion tank and the water level was raised to 600 mm above the bottom plate of the samples. Each sample remained partially submerged for nominally four days. Subsequently the tank was drained and the samples were removed from the tank and were placed in a ventilated sheltered drying area for a duration of six weeks.

The racking tests were conducted in three steps i.e. 'pull', 'push', 'pull' in the test rig shown in Figure 9. For the first pull and the push tests the loads applied were within the serviceability limits of the samples. For the last pull test, the load was slowly increased until failure of the test specimen. Failure was defined for this test programme as the displacement at which the maximum load able to be resisted by the wall was reached.

The results of the tests showed that flooding did not have any significant effect on the racking strength of the OSB wall sheet bracing. There was a nominal strength reduction of 10% for the HDF wall sheet bracing when tested after wetting and drying cycle.

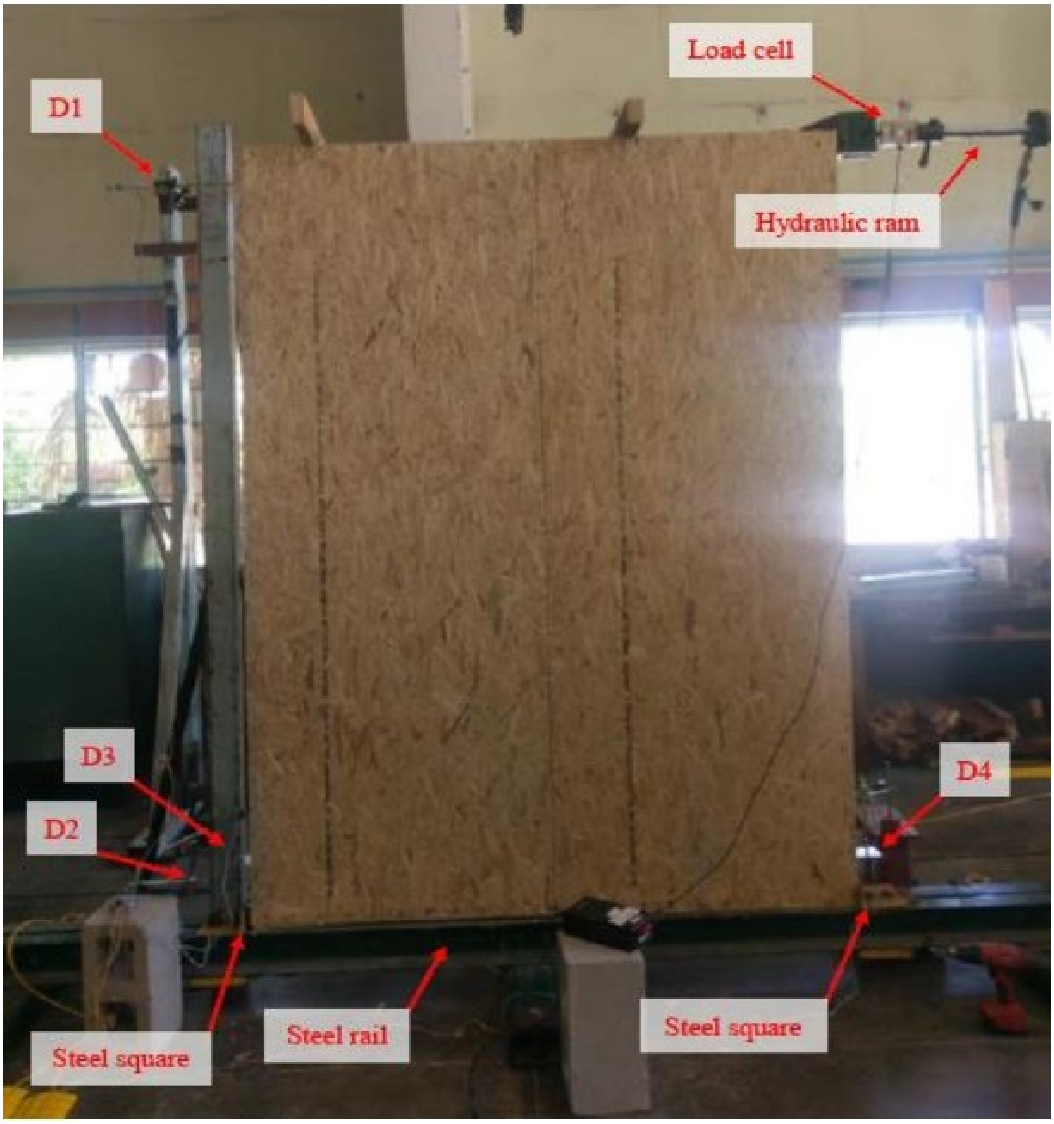

FIGURE 9: OSB TEST SAMPLE IN TEST RIG

Test Type 3 (Timber Joists)

Test Type 3 was designed to assess the structural adequacy of manufactured timber 'I' section joists following inundation and subsequent drying. Strength was tested at three stages: dry before immersion, wet immediately after immersion and dry after drying following immersion.

The samples had an 'I' shape and were made with a top and bottom flange joined by an OSB vertical web. They were tested in four point bending: simply supported at the ends with point loads applied at 1/3 of the span from each end (Figure 10). Forty-eight specimens were tested in total with 16 being dry through the entirety of the program, 16 were tested wet immediately and then the final 16 were tested after a wetting and drying cycle.

The test results indicated that flooding did not have any adverse impact on the bending and shear strength of the joists when tested in re-dried condition. There was a greater (nominally 46%) reduction in average maximum load observed between samples that remained dry to those that were inundated and tested whilst wet.

These results suggest that the samples whilst in the wet stage may be compromised due to reduced strength capacity and stiffness. However, if allowed to dry then the specimen could recover to nominally 96% of average strength capacity and stiffness. Provided excessive permanent sag deflection had not been recorded, or the joist had not been overloaded due to temporary relocation of furniture, replacement is not considered to be necessary by this research.

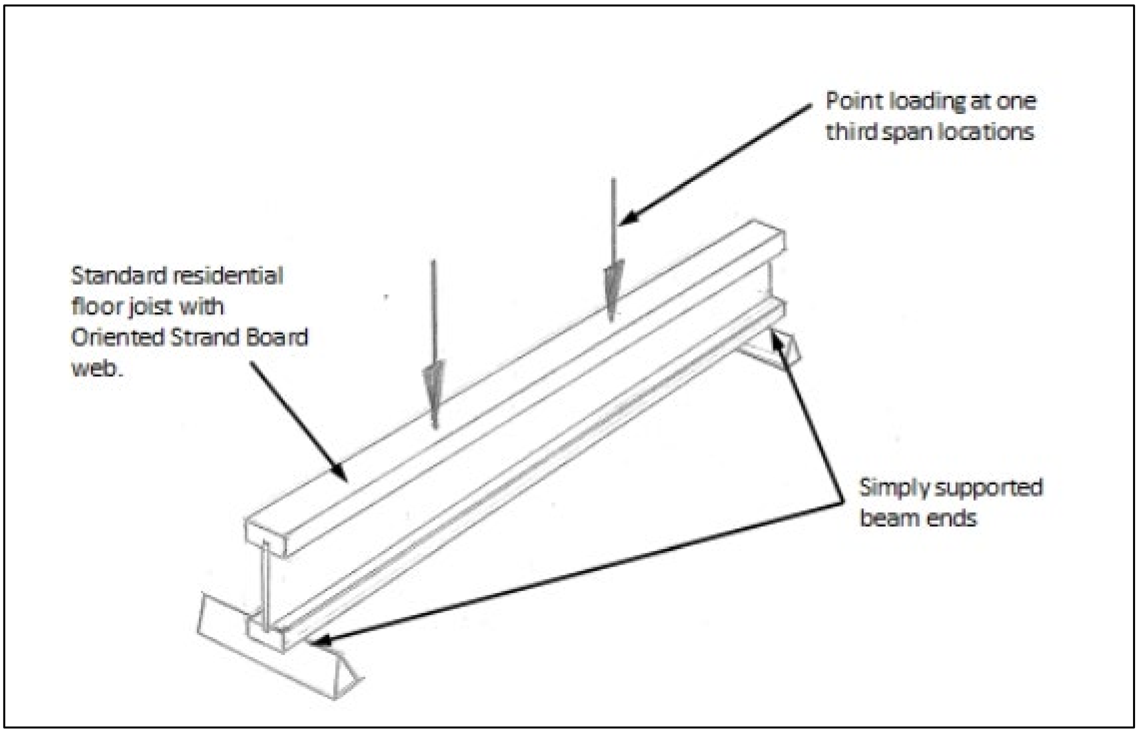

FIGURE 10: SCHEMATIC DIAGRAM OF ENGINEERED TIMBER JOIST IN FOUR POINT BENDING

Summary of Experimental Program Findings

The results showed that flooding and subsequent drying did not have any significant effect on most of these materials. The bond strength of the ceramic tiles to their substrate, and the racking strength of the OSB wall sheet bracing after drying were unaffected. Results demonstrated that there was no significant variation in stiffness of the OSB and HDF wall sheet bracing specimens that were exposed to floodwater to those that were not exposed to the flooding.

However, there was a significant reduction (46%) in load carrying capacity of the timber joists when tested in the wet condition. Moreover, the stiffness of floor joist samples was significantly reduced when in the wet state. These results suggest that the floor joist samples whilst saturated may be compromised due to reduced strength and stiffness.

It was also observed that the moisture content level in all the tested components returned to close to pre-inundation level within a week of the test.

COSTING OF MITIGATION STRATEGIES AND DEVELOPMENT OF FLOOD VULNERABILITY MODELS FOR MITIGATED BUILDING TYPES

Selection of key storey types

Five typical residential storey types have been selected for the balance of the research which are a subset of the schema proposed earlier in this report. Key characteristics of these storey types are presented in Table 3 with descriptions in the following sections. Detailed information on the buildings to component level are provided in Maqsood et al. (2016).

TABLE 3: CHARACTERISTICS OF SELECTED STOREY TYPES

Storey Type	Construction period	Bottom floor system	Fit-out quality	Storey height	Internal wall material	External wall material	Photo
1	Pre-1960	Raised Timber	Low	2.7m	Timber	Weather-board	
2	Pre-1960	Raised Timber	Low	3.0m	Masonry	Cavity masonry	
3	Pre-1960	Raised Timber	Standard	2.4m	Masonry	Cavity masonry	
4	Post-1960	Raised Timber	Standard	2.4m	Plasterboard	Brick veneer	

5	Post-1960	Slab-on-grade	Standard	2.4m	Plasterboard	Brick veneer	

Storey Type 1: Timber Frame (raised floor)

Storey Type 1 is an older (pre-1960) light frame construction made of hardwood timber that is supported on piers made of brick or timber. This type of construction is most common in northern Australia and is supported on both short (low-set) and tall (high-set) piers. The underfloor area is used to cool the building through ventilation, to protect the main structure from termite attack and to reduce flood vulnerability in some localities (for high-set). The typical floor system is made of timber joists and bearers with hardwood strip flooring. Exterior cladding is generally hardwood weatherboards while the lining to the interior wall is softwood timber boarding. The ceiling consists of timber boarding and/or plasterboard attached to timber battens. A typical building plan and elevations are presented in Appendix A.

The raised floor is critical to avoid damage due to low levels of flooding. However, because of its light weight and lack of effective connection to the foundation, this storey type is most vulnerable to flash flooding and could exhibit velocity related damage. This could result in flotation and displacement of the structure, and in the worst case, total destruction. A recent example of this type of damage was seen in Dungog, NSW, where four houses were washed away (Wehner and Maqsood, 2015). More examples of this type of damage were seen in Grantham, Queensland, during the 2010-11 floods (Wehner et al. 2012).

Storey Type 2: Cavity Masonry - Victorian Terrace (raised floor)

Storey Type 2 is an older (pre-1960) Victorian terrace made of masonry. This type of construction is quite common in older inner city areas of major Australian cites, particularly in Sydney and Melbourne. The typical floor system is made of timber joists and bearers with hardwood floor boards raised to 0.3m above the ground. Exterior walls are made of cavity masonry while interior walls are made of a single leaf of rendered brick. The ceiling is made of plasterboard attached to timber battens. A typical building plan and elevations are presented in Appendix B.

Because of the masonry walls this storey type is considered to be less vulnerable to flood damage as much of the damage can be repaired by washing and cleaning.

Storey Type 3: Cavity Masonry (raised floor)

Storey Type 3 represents pre-1960 cavity masonry construction. This type of construction is quite common in all Australian cites. The substructure consists of reinforced concrete strip footings with chipboard flooring raised to 0.75m off the ground. Exterior walls are made of cavity masonry while the interior walls are made of a single leaf of rendered brick. The ceiling is made of plasterboard attached to timber battens. A typical building plan and elevations are presented in Appendix C.

Storey Type 4: Brick Veneer (raised floor)

Storey Type 4 represents relatively newer (post-1960) brick veneer construction. This type of construction is very common in all Australian cites and is comprised of timber frame construction with brick cladding. The substructure consists of reinforced concrete strip footings. The typical floor system is made of timber joists and bearers with chipboard flooring raised to 0.75m off the ground. Exterior cladding is comprised of a single leaf of brick wall attached to the timber frame while lining to the interior face of the timber frame is plasterboard. The ceiling is made of plasterboard attached to timber battens. A typical building plan and elevations are presented in Appendix D.

Storey Type 5: Brick Veneer (slab-on-grade)

Storey Type 5 represents the typical new (post-1960) slab-on-grade residential construction made of brick veneer. This type of construction is the most common new construction type in all Australian cites and is comprised of timber frame construction with brick cladding. The substructure consists of a reinforced concrete slab on the ground. Floor finishes are typically tiles and carpets. The exterior cladding is a single leaf of brick wall attached to the timber frame while lining to the interior face of the timber frame is plasterboard. The ceiling is made of plasterboard attached to timber battens. A typical building plan and elevations are presented in Appendix E.

Development of costing modules for selected mitigation strategies

Costing modules have been developed by quantity surveying specialists to estimate the cost of implementing all appropriate mitigation strategies for these five storey types (see Table 4). Table 5 provides an example of the types of measures that were costed for the wet floodproofing of Storey Type 1. Further examples are provided in reporting by Maqsood et al. (2016a).

TABLE 4: COST OF IMPLEMENTING FLOOD MITIGATION STRATEGISES TO EXISTING BUILDINGS FOR SELECTED STOREY TYPES (2016 DOLLARS)

Storey Type	Elevation (Extending the walls)	Elevation (Building a second storey)	Elevation (Raising the whole house)	Relocation	Flood Barriers (Permanent)		Flood Barriers (Temporary)			Dry Flood-proofing	Wet Flood-proofing	
					1.0m high	1.8m high	0.9m high	1.2m high	1.8m high		Existing structure	Substantial Renovation
1	N/A	N/A	$78,200		N/A	N/A	N/A	N/A	N/A	N/A	$11,700	$68,000
2	N/A	$213,500	N/A	N/A	$133,500	$177,600	$62,500	$111,800	$136,300	N/A	$15,400	$56,600
3	$397,700	$429,700	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$17,400	$104,300
4	N/A	$405,200	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$15,500	$140,000
5	N/A	$431,000	N/A	N/A	$154,300	$208,300	$164,600	$144,100	$176,200	$154,320	$17,400	$149,800

TABLE 5: BUILDING COMPONENTS AND WET FLOODPROOFING MEASURES FOR STOREY TYPE 1

No.	Component	Description	Flood proofing measure: Wet floodproofing (replace original component with)	
			to existing building	during substantial reconstruction
1	Substructure	250mm square reinforced concrete piers embedded 1.0m into ground and bearing on 400x400x200mm concrete pads. External piers painted. Antcaps installed.		
2	Substructure	Timber lattice enclosing underfloor space		
3	External stairs	Painted hardwood entry stairs, 1500mm rise, 1400mm wide o/a complete with painted timber handrail		
4	External stairs	Painted hardwood rear stairs, 1500mm rise, 1200mm wide o/a complete with painted timber handrail		
5	Timber floor structure	125x45 hardwood joists @ 450ctrs on 125x75 hardwood bearers @ 2000 ctrs		
6	Timber flooring	19mm thick T&G hardwood strip flooring		
7	Timber wall framing	90x45 hardwood studs @ 450 ctrs, similar top & btm plates, 2 rows of noggings		
8	Exterior cladding	Hardwood weatherboards, painted		
9	General lining to interior of exterior walls and interior walls	Softwood timber boarding 9mm thick		
10	Lining to bathroom, toilet and laundry walls	Fibre cement sheeting		
11	Lining to kitchen walls	Fibre cement sheeting		
12	Skirting boards	Moulded softwood skirting, paint finish		Aluminium skirting (may require extra packing for attaching the skirting properly due to 30mm gap)
13	Cornices	Preshaped plaster cornice		
14	Ceiling	Softwood timber boarding 9mm thick to lounge, kitchen and bedrooms, 13mm plasterboard to other areas all on timber battens		
15	Timber roof structure	Hardwood cut roof framing		
16	Roofing	Colourbond corrugated iron roofing and flashings screw fixed to timber battens		
17	Wall insulation	Fibreglass batts (thermal to exterior walls, sound to interior walls)		Polystyrene boards/Rigid closed cell board (using nails so that insulation can be removed from inside the house following a flood)
18	Roof insulation	Fibreglass batts		
19	Windows	Timber, single glazed, painted, 50% casement, 50% sash		
20	Window surrounds	Softwood moulded timber		
21	Window sills	Painted softwood moulded sills		
22	External doors	Solid core timber front door with deadlock, ditto to rear door, varnish finish		
23	External door frames	Hardwood timber door frames, varnish finish		Aluminium door frame, paint finish
24	Internal doors	Hollowcore doors, paint finish		
25	Internal door frames	Softwood timber door frames, paint finish		Aluminium door frame, paint finish
26	Eaves lining	Fibre cement sheeting with timber beading at sheet joins		

27	Guttering and downpipes	Painted galvanised rainwater goods		
28	Floor covering (bedrooms)	Carpet with rubber underlay		Polyurethane finished floorboards
29	Floor covering (bathroom, toilet, laundry)	6mm floor tiles on 4.5mm fibre cement sheet.		
30	Floor covering (kitchen)	Linoleum tiles glued to hardboard sheet		Polyurethane finished floorboards
31	Floor covering general	Polyurethane finished floorboards		
32	Wall finishes (general)	Undercoat + 2 top coats paint		
33	Wall finishes (bathroom)	Full height wall tiles adhesive fixed to FC sheet		
34	Wall finishes (toilet)	200mm height skirt tiles, paint above		
35	Wall finishes (laundry)	0.5m2 tile splashback, 200mm height skirt tiles, paint elsewhere		
36	Wall finshes (kitchen)	Tile splashback to all benches, 800 high. Paint elsewhere		
37	Ceiling finishes	Undercoat + 2 top coats paint		
38	Bathroom joinery	Melamine covered mdf vanity, FC sheet skirting around bath.		Melamine covered mdf vanity (wall hung at 0.4m high), FC sheet skirting around bath.
39	Bathroom basin and tapware	Ceramic basin, connecting hydraulics and chrome taps		
40	Bath	Enamelled steel and chrome taps		
41	Bathroom fixtures	Chrome towel rail and soap dish		
42	Shower recess	Frameless glass 0.9m2 shower cubicle and chrome taps		
43	Shower recess hob	Masonry hob finished to accept waterproofing and tiles		
44	Shower water proofing	Paint-on waterproof membrane		
45	Toilet fixtures	Ceramic dual flush toilet and connecting hydraulics, chrome toilet paper holder		
46	Laundry fixtures	Stainless steel tub with chrome taps, chrome taps for washing machine		
47	Laundry joinery	Melamine covered mdf broom cupboard	Melamine covered mdf high level wall mounted cabinets 1.8m long	Melamine covered mdf high level wall mounted cabinets 1.8m long
48	Kitchen joinery	Melamine covered mdf kitchen under bench cupboards, high level cupboards, laminex covered benchtops		Steel shelves, cabinets and benchtop
49	Kitchen fixtures	Stainless steel basin and chrome taps		
50	Kitchen appliances	Gas cooktop, electric underbench oven, dishwasher, electric rangehood	Gas cooktop, dishwasher, electric rangehood, electric oven at 0.9m height	Gas cooktop, dishwasher, electric rangehood, electric oven at 0.9m height
51	Mechanical	Bathroom extraction fan		
52	Mechanical	2.5hp A/C system mounted back to back with external unit on ground	2.5hp A/C external unit mounted on brick pier (1.2m high, 0.35m wide and 1.2m long)	2.5hp A/C external unit mounted on brick pier (1.2m high, 0.35m wide and 1.2m long)
53	Mechanical	Check gas supply to kitchen		
54	Electrical - lighting	Central ceiling mounted light fitting (10 No) + ceiling mounted fluorescent fitting to kitchen		
55	Electrical lighting	Wall mounted light switches (11 No)		
56	Electrical exterior lighting	Two No external sensor lights mounted under eaves		
57	Electrical - power	11 No. double GPO	11 No. double GPO at 1.2m above floor level	11 No. double GPO at 1.2m above floor level
58	Electrical - power	Meter box		

59	Electrical - general	Test electrical cabling for faults (item) (assume no rewiring necessary for all depths)		
60	Hydraulic - HWS	Electrical 250l HWS mounted externally on ground	Electrical 250l HWS mounted externally on brick pier (1.2m high, 0.35m wide and 1.2m long)	Electrical 250l HWS mounted externally on brick pier (1.2m high, 0.35m wide and 1.2m long)
61	Hydraulic - water supply piping	Copper 15mm diameter		
62	Hydraulic - sanitary drainage	100mm vitreous clay		
63	Hydraulic - SW drainage	100mm concrete jointed pipe		
64	Window furnishing	Fabric curtains to bedroom & lounge windows. Plastic Venetian blinds to kitchen, laundry, toilet and bathroom windows.		
65	Hydraulic - SW		Installing check valve and gate valve	Installing check valve and gate valve

Development of flood vulnerability models for mitigated building types

This section summarises the outcomes of the application of the previously described mitigation strategies in the form of vulnerability models for mitigated buildings. The mitigated curves will be equal or 'lower' than the non-mitigated version representing less damage at the same level of water ingress due to the mitigation efforts.

Storey Type 1: Timber Frame (raised floor)

As described previously (Table 3) Storey Type 1 is a pre-1960 light frame construction made of hardwood timber which is supported on piers made of brick or timber. For Storey Type 1 the elevation technique to raise the whole structure is considered to be the most appropriate (USACE, 2000). Figure 11 presents a comparison of the vulnerability of Storey Type 1 before and after elevation. A significant reduction in damage cost is assessed by implementing this strategy in which the structure is elevated by 2.5m.

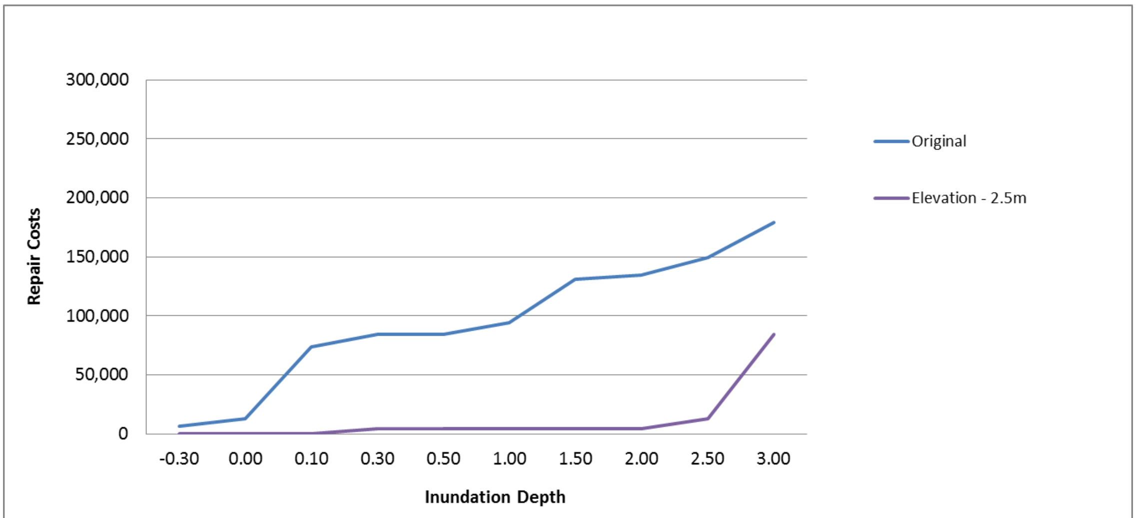

FIGURE 11: VULNERABILITY CURVES FOR STOREY TYPE 1 - ORIGINAL AND ELEVATED

Relocation is relatively easy for Storey Type 1. As the structure is moved outside the floodplain to an elevated location, theoretically the resultant risk is reduced to zero. Therefore, the cost of relocation will be considered in the cost benefit analysis and no graph is presented.

Dry floodproofing is not recommended for timber frame structures and for structures with raised timber floors. These types of structure can be susceptible to significant lateral and uplift (buoyancy) forces (USACE, 1988). Therefore, dry floodproofing is not considered an appropriate strategy for Storey Type 1.

Wet floodproofing is considered appropriate for all the storey types studied in this report. This strategy can be implemented at two different stages i.e. existing state or during substantial renovation or reconstruction. The wet floodproofing strategies have been evaluated and costed through engagement of a professional quantity surveying consultant. Table 5 provides detail of the wet floodproofing strategy for different building components for Storey Type 1 with the two construction regimes described above. The resultant reduction in flood damage due to wet floodproofing is demonstrated in Figure 12. It is observed that there is limited benefit due to wet floodproofing existing buildings but greater benefits can be realised when this strategy is applied during reconstruction or substantial renovation.

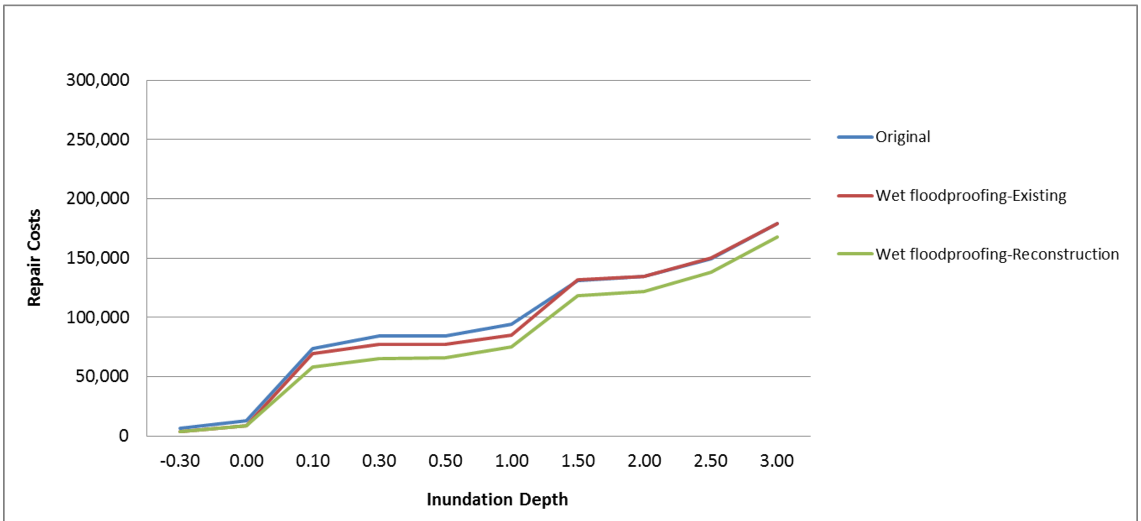

FIGURE 12: VULNERABILITY CURVES FOR STOREY TYPE 1 – ORIGINAL AND WET FLOODPROOFED

The cost of flood barriers increases with the increase of the height of barriers. Therefore, these are not considered economically suitable to be used for Storey Type 1 as this storey type has floors at or above 0.7m from the ground level. Consequently, this strategy has not been applied to this storey type.

Storey Type 2: Cavity Masonry - Victorian Terrace (raised floor)

Storey Type 2 is an older (pre-1960) Victorian terrace made of masonry. Changing the use of an existing ground floor and constructing a second storey is considered an appropriate elevation mechanism for this storey type. Figure 13 presents a comparison of the vulnerability curves for Storey Type 2 before and after elevation through creation of a new storey. A significant reduction in damage cost is achieved by implementing this strategy.

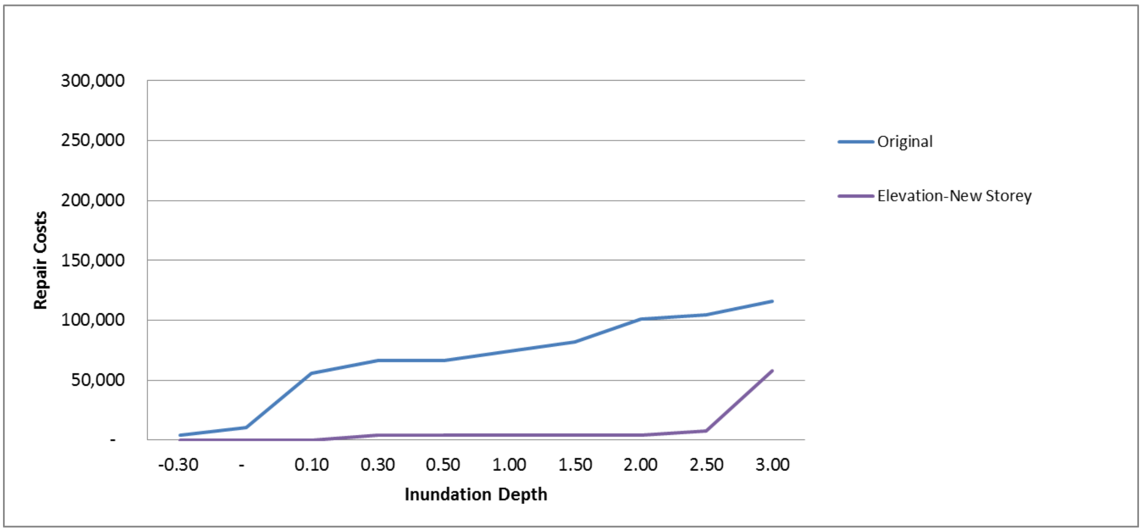

FIGURE 13: VULNERABILITY CURVES FOR STOREY TYPE 2 – ORIGINAL AND ELEVATED (NEW STOREY)

Wet floodproofing is considered suitable for this storey type. As mentioned earlier this strategy can be implemented during two different construction regimes i.e. existing state before any event and during substantial renovation or reconstruction after an event. It is observed in Figure 14 that there is limited benefit from a wet floodproofing strategy for this storey type.

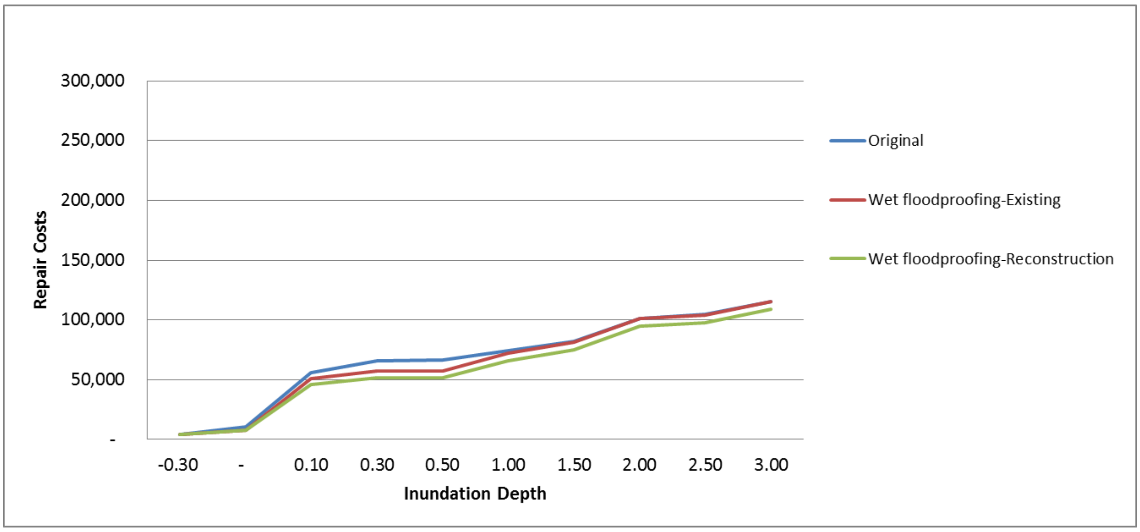

FIGURE 14: VULNERABILITY CURVES FOR STOREY TYPE 2 - ORIGINAL AND WET FLOODPROOFED

Figure 15 presents a comparison of the vulnerability of Storey Type 2 before and after using flood barriers. The step-wise functions demonstrate the limited application of flood barriers as these are only able to protect the property up to their designed height.

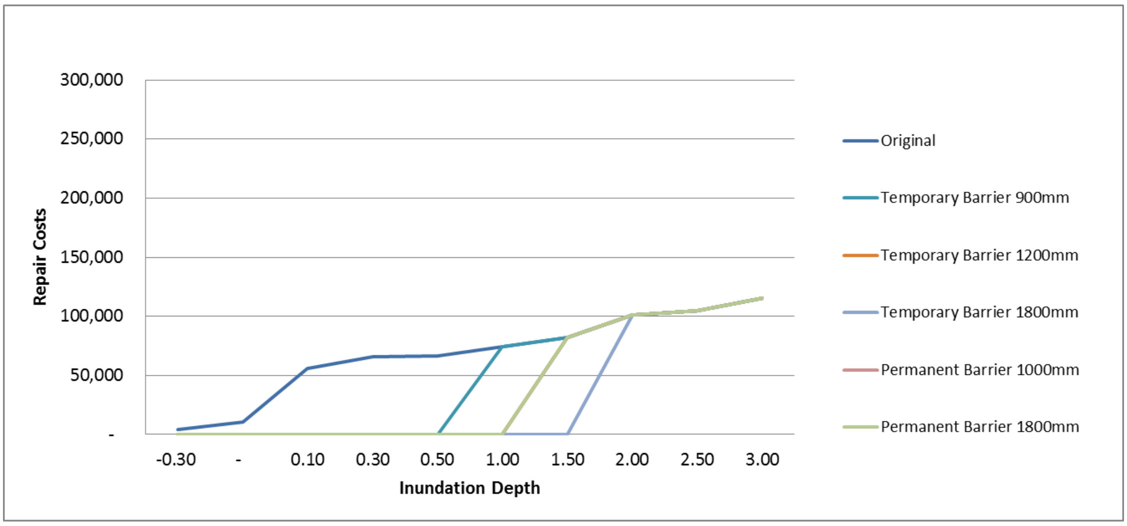

FIGURE 15: VULNERABILITY CURVES FOR STOREY TYPE 2 - ORIGINAL AND FLOOD BARRIERS

Storey Type 3: Cavity Masonry (raised floor)

Storey Type 3 represents a pre-1960 cavity masonry construction. A change of ground floor usage and construction of a new storey above is an appropriate elevation strategy for this Storey Type. Figure 16 presents a comparison of the vulnerability of Storey Type 3 before and after elevation. Again, a significant reduction in damage cost can be achieved by implementing this strategy.

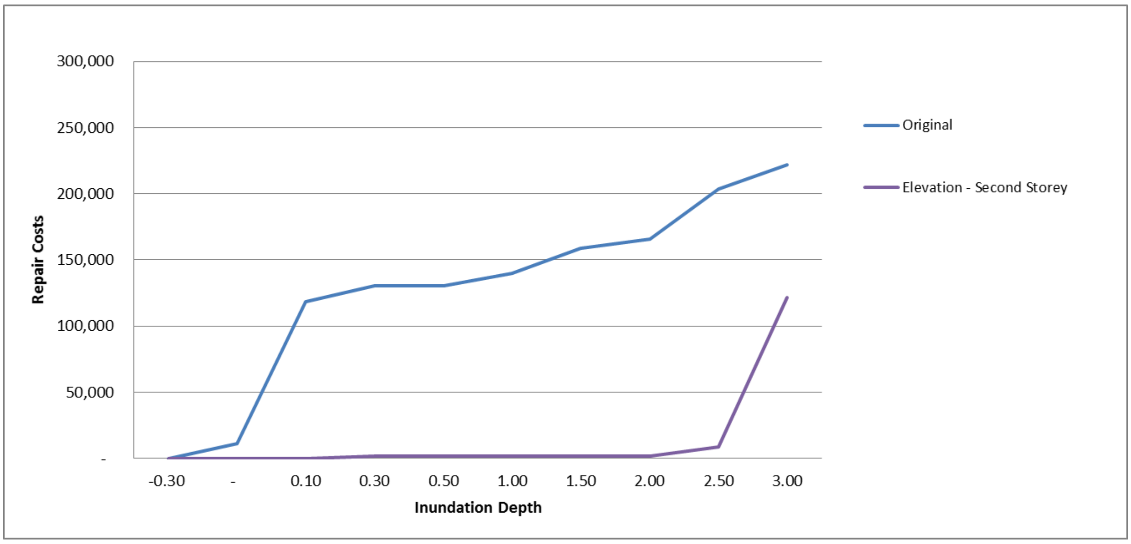

FIGURE 16: VULNERABILITY CURVES FOR STOREY TYPE 3 - ORIGINAL AND ELEVATED

Wet floodproofing during existing state and during substantial renovation or reconstruction has been evaluated for this storey type. The resultant reduction in flood damage due to wet floodproofing is demonstrated in Figure 17 where effecting the wet floodproofing measures during reconstruction or renovation clearly provides greater benefit.

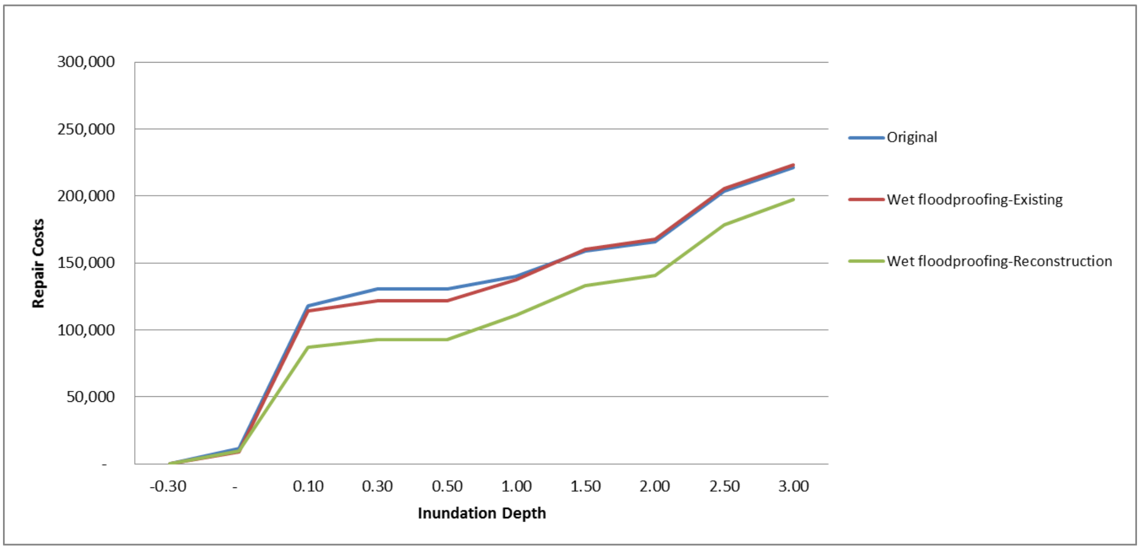

FIGURE 17: VULNERABILITY CURVES FOR STOREY TYPE 3 - ORIGINAL AND WET FLOODPROOFED

Dry floodproofing was not considered as a mitigation strategy for this Storey Type as it is not recommended for structures with raised timber floors, as they may be susceptible to uplift (buoyancy) forces (USACE, 1988). Flood barriers are also not effective for properties with raised floors and were not considered as a strategy for this storey type.

Storey Type 4: Brick Veneer (raised floor)

Storey Type 4 represents relatively newer (post-1960) brick veneer construction. The ground floor usage is changed and a new storey constructed above as an elevation technique. Figure 18 presents a comparison of vulnerability of Storey Type 4 before and after elevation. Again, a significant reduction in damage cost is effected by implementing this strategy.

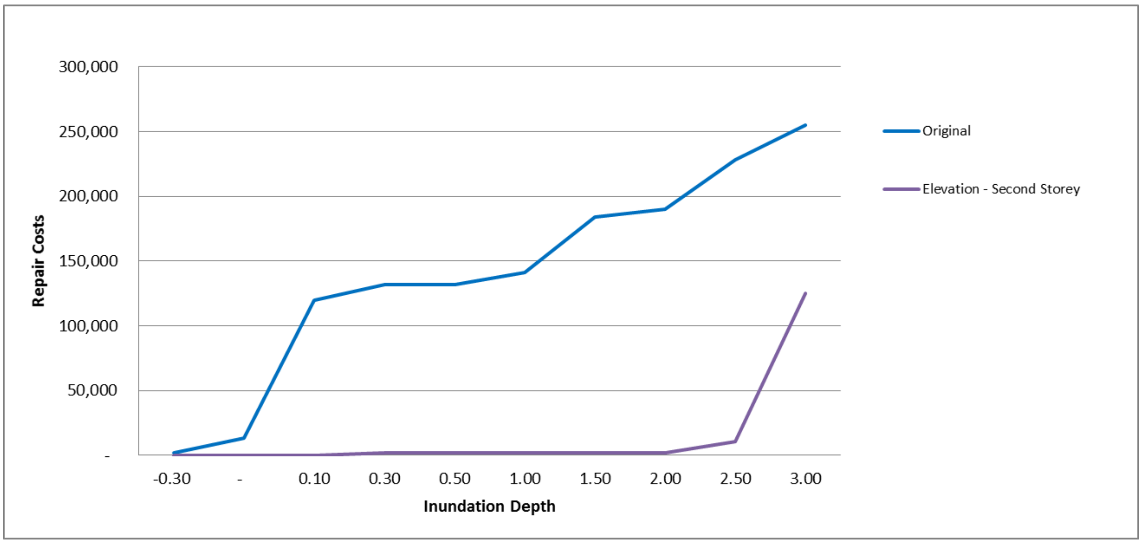

FIGURE 18: VULNERABILITY CURVES FOR STOREY TYPE 4 - ORIGINAL AND ELEVATED

Wet floodproofing has also been evaluated for this Storey Type. The resultant reduction in flood damage due to wet floodproofing is demonstrated in Figure 19 with only minor benefit observed.

Dry floodproofing has not been assessed for Storey Type 4 as it may lead to buoyancy forces (USACE, 1988) and a lack of overall stability. Flood barriers are also not considered effective for properties with raised floors and this strategy has not been modelled for this storey type.

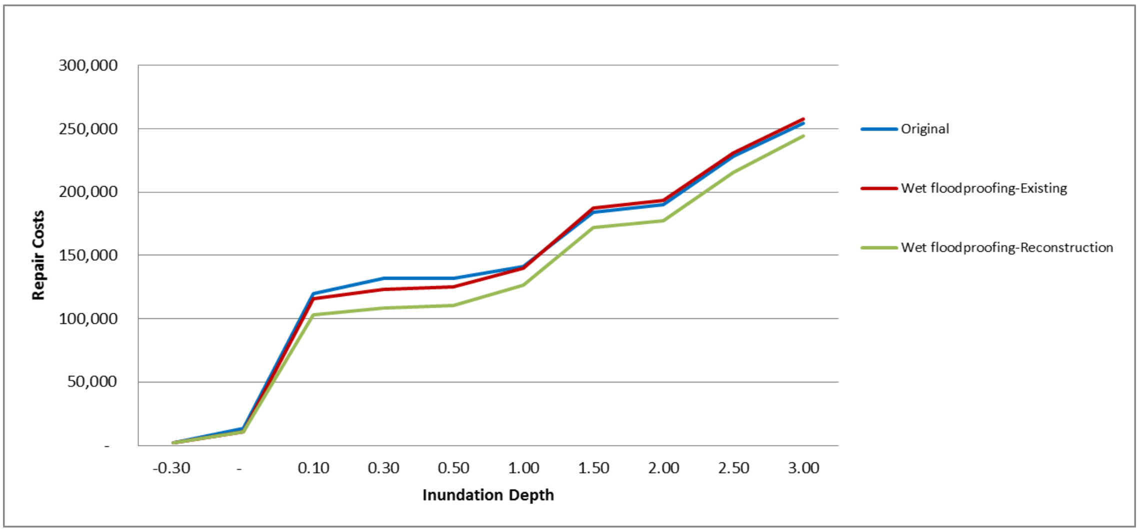

FIGURE 19: VULNERABILITY CURVES FOR STOREY TYPE 4 - ORIGINAL AND WET FLOODPROOFED

Storey Type 5: Brick Veneer (slab-on-grade)

Storey Type 5 represents the typical new (post-1960) slab-on-grade residential construction made of brick veneer. For elevation of Storey Type 5 the ground floor usage is changed and an additional storey added above. Figure 20 presents a comparison of vulnerability of Storey Type 5 before and after elevation. As in previous storey types, a significant reduction in damage cost is modelled through the implementation of this strategy.

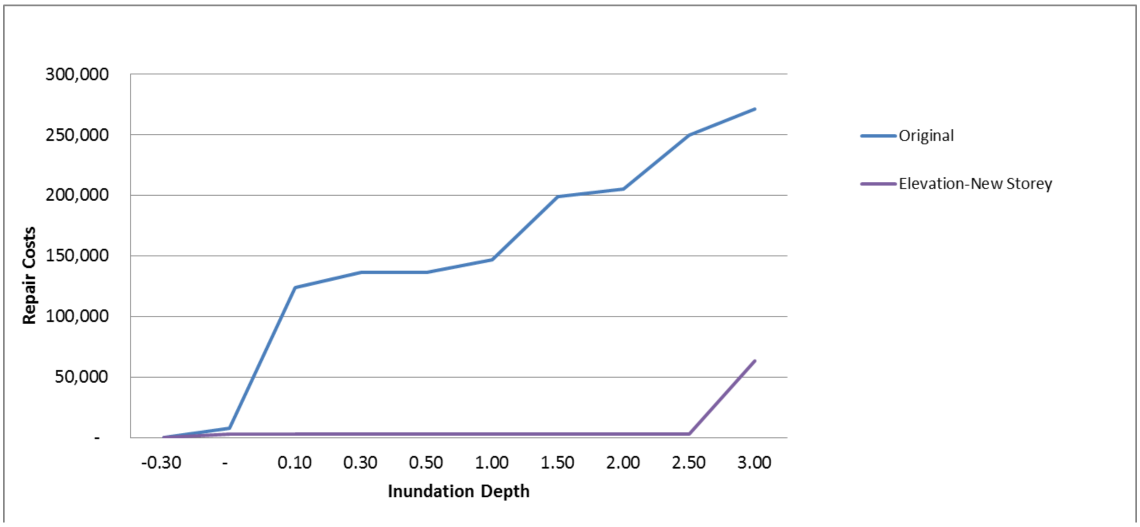

FIGURE 20: VULNERABILITY CURVES FOR STOREY TYPE 5 - ORIGINAL AND ELEVATED

Wet floodproofing has been evaluated for this storey type with the curves presented in Figure 21. The reduction in flood damage is again larger when wet floodproofing is undertaken during renovation or reconstruction.

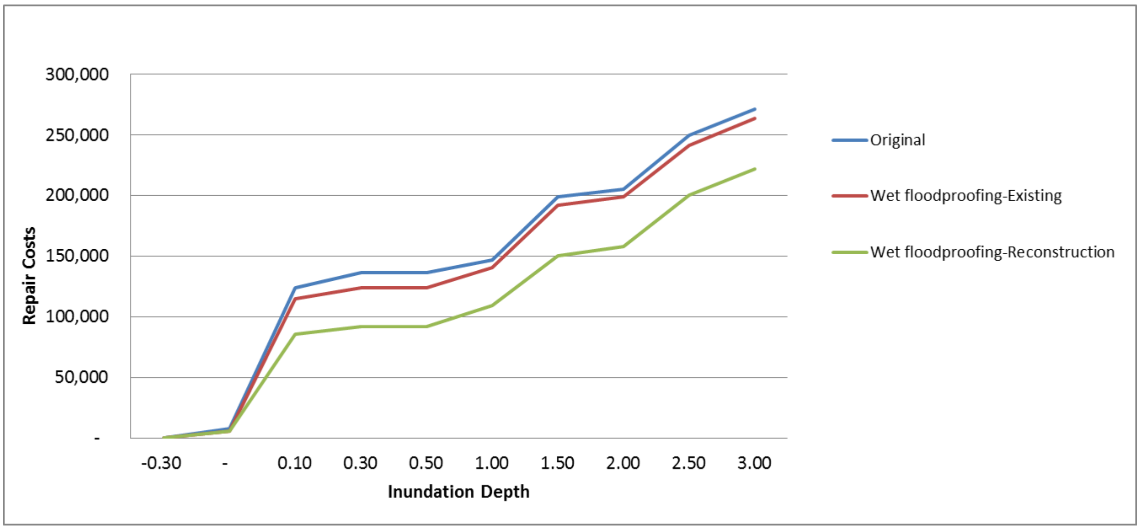

FIGURE 21: VULNERABILITY CURVES FOR STOREY TYPE 5 - ORIGINAL AND WET FLOODPROOFED

Figure 22 presents a comparison of vulnerability for Storey Type 5 before and after using flood barriers. A range of types of barriers has been chosen and the step wise functions demonstrates that flood barriers are very effective but only up to their design height.

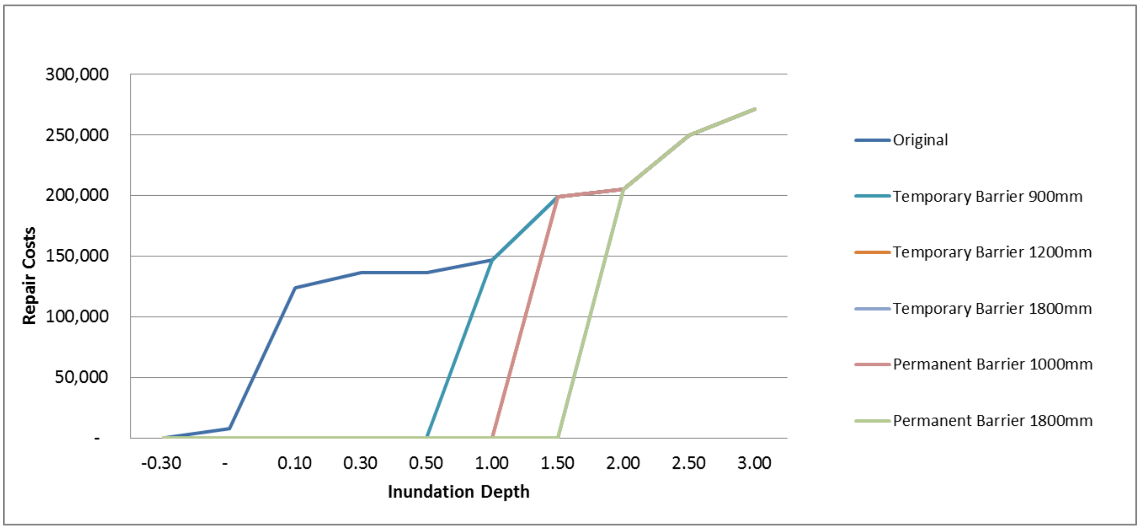

FIGURE 22: VULNERABILITY CURVES FOR STOREY TYPE 5 - ORIGINAL AND FLOOD BARRIERS

Dry floodproofing has been evaluated for Storey Type 5. It is generally not recommended for flood depths exceeding one metre based on tests 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. Figure 23 presents a comparison of vulnerability of Storey Type 5 before and after dry floodproofing the structure up to 1m.

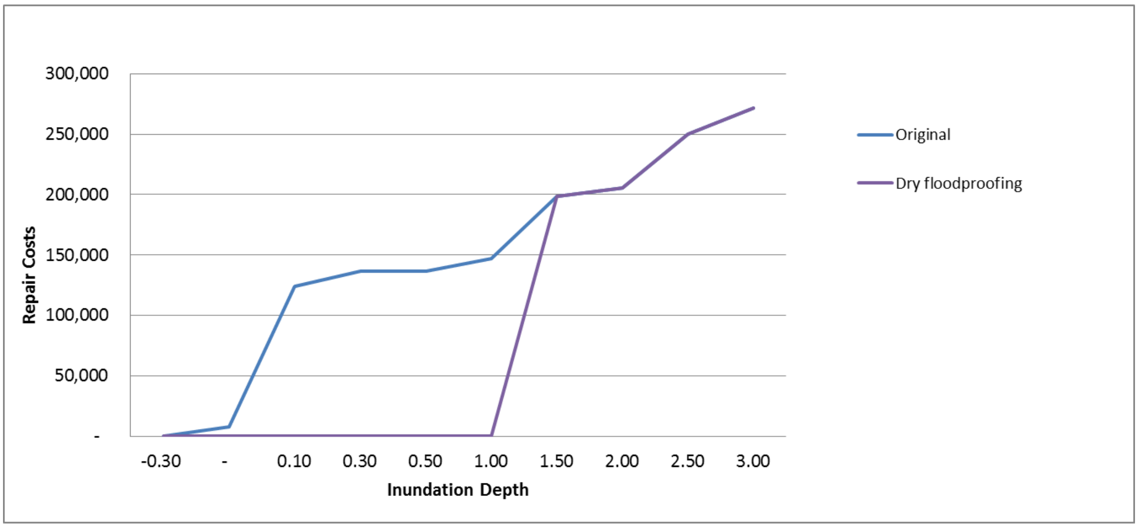

FIGURE 23: VULNERABILITY CURVES FOR STOREY TYPE 5 - ORIGINAL AND DRY FLOODPROOFED

BENEFIT VERSUS COST ANALYSES

Retrofit options entail an investment that will realise a benefit over future years through reduced average annualised loss caused by severe flood exposure. Decisions to invest in reducing building vulnerability, either through asset owner initiatives or the provision by government or the insurance industry incentives, will depend upon the benefit versus cost of the retrofit.

In this research, retrofit options were assessed through a consideration of a range of severity and likelihood of flood hazard covering a selection of catchment types. The work provides information on the optimal retrofit types and design levels in the context of Australian construction costs and catchment behaviours. The studies also varied in terms of mitigation level: community level mitigation, aggregated building level mitigation and individual building level mitigation. These are each presented in the following sections.

Benefit versus cost analysis framework

The application of the benefit versus cost analysis in this study was to evaluate the cost-efficiency of flood risk mitigation investment for a variety of mitigation options for typical Australian residential buildings. The benefit versus cost analysis comprised four steps as presented in Figure 24 and described below.

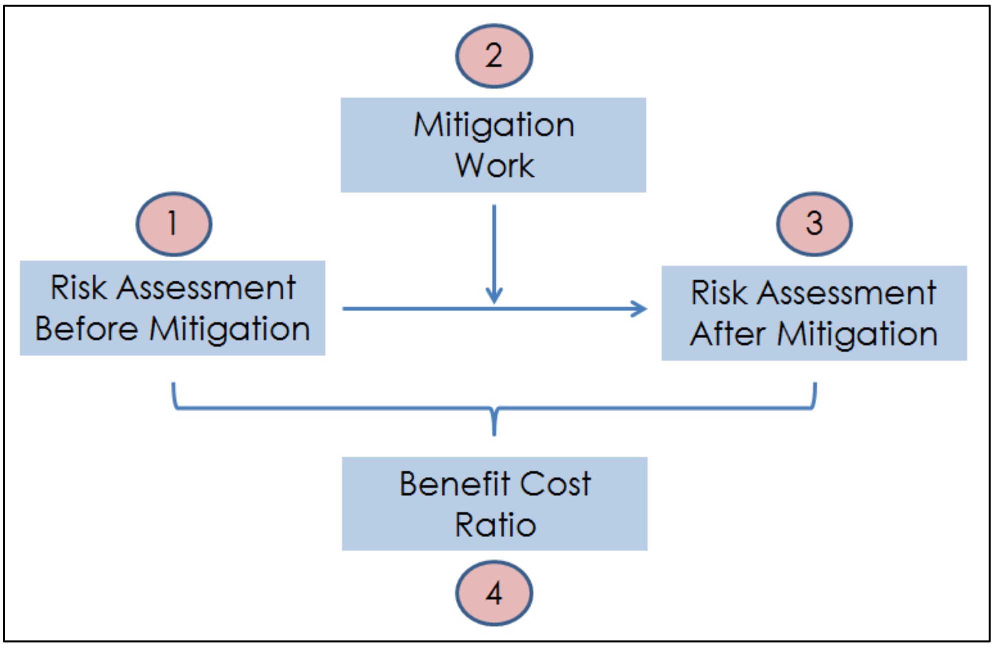

FIGURE 24: COST VERSUS BENEFIT ANALYSIS FRAMEWORK (ADAPTED FROM MECHLER, 2005)

1. Risk Assessment before mitigation: at this step risk was calculated in terms of conditional loss ($) based on existing building stock (unretrofitted).
2. Mitigation work: this was the investment ($) to reduce potential impacts assessed in the first step. It was comprised of the costs of conducting the mitigation work on the relevant properties.
3. Risk Assessment after mitigation: at this step risk was again calculated incorporating the effects of the mitigation investment. There is typically a reduction of loss ($) compared to the pre-mitigation state. This reduction in loss ($) was considered to be the benefit arising from the investment.
4. Benefit Cost Ratio: finally, economic effectiveness of the mitigation investment was evaluated by comparing benefits and costs. Costs and benefits accumulating over time needed to be discounted to make current and future effects comparable as any money spent or saved today has more value than that realised from expenditure and benefits in the future. This concept is termed Time Value of Money. Future values therefore need to be discounted by a discount rate representing the loss in value over time. A Benefit Cost Ratio of 1.0 or more suggests the mitigation investment was an economically viable decision.

Launceston Benefit versus Cost Analysis: Community Level Mitigation

Hazard

In this study, the hazard is defined in terms of flood depth above ground floor level. The hazard information for 20 to 500 year ARIs was provided by the LCC (2011). To make this study more rigorous and to include rarer events in the analysis the same consultant that provided the flood study to LCC was engaged to develop the hazard maps for the 1,000 year ARI and PMF events (BMT WBM, 2016). The hazard information utilised in the study included the flood extents and peak flood levels for all the ARIs up to the PMF (100,000 year ARI). Figure 25 shows the modelled flood extents for the events from the 20 year ARI to the PMF.

Exposure

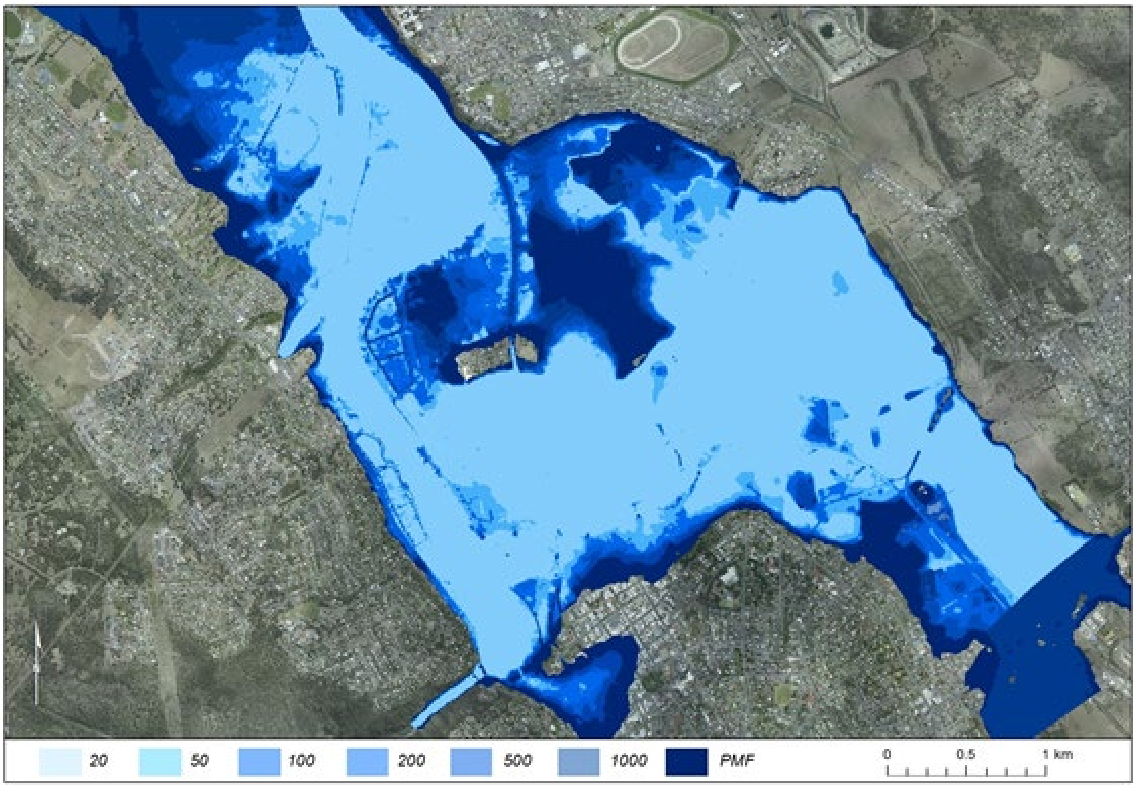

FIGURE 25: LAUNCESTON FLOOD EXTENTS FOR SELECTED RECURRENCE INTERVALS

This study focused on assessing impacts of floods on buildings, businesses and people. The exposure database was compiled for all buildings (2,656 in total) within the mapped PMF extent by sourcing building attributes from GA's National Exposure Information System - NEXIS (GA, 2017). This database was supplemented by a desktop study utilising Google street view imagery to record additional building attributes. Floor height information was provided by the LCC for all buildings within the 500 ARI extent map. For the remaining buildings exposed to rarer events a desktop study was conducted to visually assess floor height for each building.

Figure 26 shows the buildings within the PMF flood extent map for which building level attributes were compiled in the exposure database.

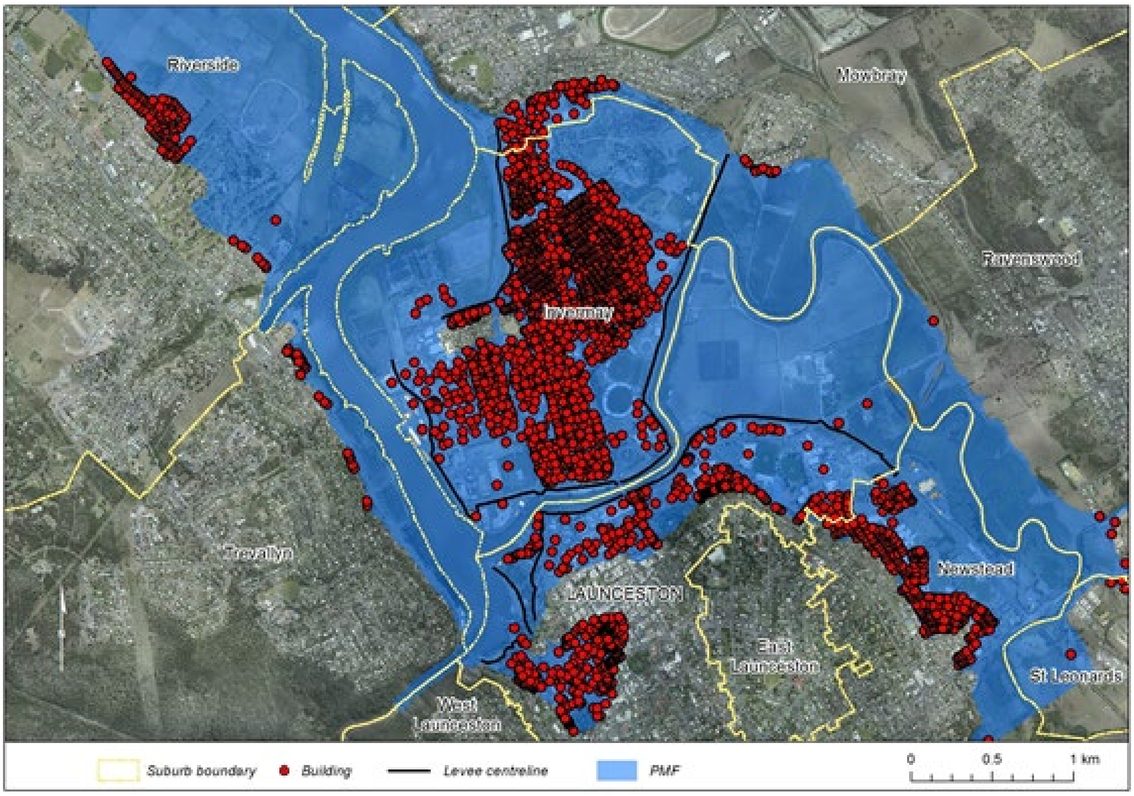

FIGURE 26: BUILDINGS WITHIN THE PMF FLOOD EXTENT

Vulnerability

Vulnerability models (also known as stage-damage curves) were sourced from the outcomes of a number of research projects that GA has undertaken in the last six years to facilitate flood risk assessment. The outcomes of these projects included flood vulnerability models for residential, commercial, industrial and community building types (29 models in total). Moreover, they also included vulnerability models for contents of residential buildings (11 models in total).

Risk

Risk can be measured as the aggregated annualised dollar loss due to building damage, essential service disruption, injury/fatality, community disruption, business inventory loss or economic activity disruption caused by hazard events over the full range of event likelihoods. For this study, risk has been assessed in terms of economic loss (or costs) from building damage, contents damage, clean-up cost, rental income loss, cost of business interruption and fatalities due to inundation. Table 6 lists the components for which losses have been estimated in this study in 2016 dollar values for the residential and non-residential sectors.

Information related to the duration of household interruption was sourced from the 2011 post-flood household surveys conducted by GA in Brisbane and Ipswich (Canterford, 2016a). The outcomes of business survey conducted after the 2013 floods in Bundaberg were utilised to assess duration of interruption, average loss of income, average loss of stock, average loss of inventory and average loss of turnover for the non-residential sector (Canterford, 2016b). The household survey outcomes were used to assess the rental income loss for the residential sector.

TABLE 6: SOURCES OF ESTIMATED LOSS FOR THE RESIDENTIAL AND NON-RESIDENTIAL SECTORS

Residential Sector	Non-residential Sector
Building repair/rebuild costs	Building repair/rebuild costs
Contents damage cost	Clean-up cost
Loss of rental income	Loss of inventory/equipment
Clean-up cost	Loss of stock
Loss due to fatalities	Loss of income: proprietor's income
	Loss of income: turnover
	Loss of income: wage/salary

In addition, Bundaberg Regional Council provided estimates of clean-up cost based on the Council's experience after the 2013 Bundaberg floods in Queensland (Honor, 2017). These cost estimates, based on per unit area of residential and non-residential buildings, were used to assess the likely clean-up cost in Launceston. These costs did not include clean-up associated with critical infrastructure.

Likelihood of fatalities was based on the fatality model developed by Jonkman (2007) and was estimated for night time population exposure in the residential sector (worst case scenario). The value of statistical life was based on the updated value determined in the parallel CRC earthquake mitigation project (CRC, 2021b) which, in turn, was based on Abelson (2007).

Methodology and Results

For the assessment of direct losses before and after the new mitigation initiative, conditional probabilities of levee failure with increasing flood depth were used to replicate the deteriorated condition of pre-existing levees. The assessed likelihood of failure due to overtopping of the new levee system if subjected to extreme flood loads was also considered. The conditional probabilities of failure for existing levees were based on GHD (2006). The conditional probabilities after mitigation were based on the assumption that the new levee system would be able to protect the community up to the 200 ARI event and hence the community will not be affected by floods having an ARI of 200 years or less. Furthermore, it was estimated that there was a 90% chance of protection during the 500 year ARI event based on the freeboard provided on top of the 200 ARI peak flood level. Table 7 shows the adopted conditional probabilities of failure for the existing and new levee systems.

TABLE 7: ADOPTED CONDITIONAL PROBABILITY OF FAILURE FOR EXISTING AND NEW LEVEES

ARI (years)	Conditional probability of failure of existing levees	Conditional probability of failure/overtopping of new levees
100,000	100%	100%
1,000	100%	100%
500	100%	10%
200	75%	0%
100	40%	0%
50	5%	0%
20	0.05%	0%

Residential Losses

Losses in the residential sector were comprised of the building repair cost, loss of contents, rental income loss, clean-up cost and cost of fatalities.

Building repair costs were estimated at building level by applying 15 vulnerability models for residential buildings developed by GA. Each residential building (1,980 in total) was assigned an appropriate vulnerability model based on building attributes.

Residential contents losses were estimated in a similar way to the building damage. Each residential building was assigned an appropriate contents vulnerability model (from GA's suite of 11 models) based on the building typology. Building contents were defined here as occupants' belongings that might be removed from the house. Items such as kitchen built-in appliances, window furnishings and floor coverings were considered part of the building fabric and hence included in building repair costs above.

The loss of rental income was estimated for the rented residential properties which could not be rented out due to the disruption and damage caused by the floods. The proportion of rental properties was assessed to be 36.7% of total privately occupied residential buildings by using census data (ABS, 2011). Similarly the average weekly rent was assessed to be $238 per property from the ABS census data for Launceston.

The duration of disruption or the time the properties could not be rented out was considered to be dependent on the severity of the flood which was measured as the inundation depth above ground floor. The duration of disruption for six categories of flood severity (or inundation depths) was based on work by Canterford et al. (2016a).

The cost of clean-up was estimated for the residential properties by using per unit area clean-up cost recorded by the Bundaberg Regional Council during the 2013 Bundaberg floods. The clean-up cost during the Bundaberg floods to residential sector was reported to be $5.12 per square meter (Honor, 2017). The total residential ground floor area affected by each hazard event was calculated by overlaying the flood footprint of each event on the building footprints.

The number and cost of fatalities was estimated at midnight as the worst case scenario when the entire population in the study area was assumed to be at home and exposed to the potential danger of flooding.

The number of fatalities was estimated by using the fatality rate functions developed by Jonkman (2007). The fatality rate is defined as the probability of a person dying in a house due to an inundation depth of *h* meters.

Non-residential Losses

Losses to the non-residential sector were contributed by the building repair cost, loss of stock, loss of inventory, loss of income, clean-up cost, and loss of turnover. The number of affected non-residential buildings was estimated by overlaying the flood footprint maps for each hazard event on building footprint maps. There were 676 non-residential buildings that were affected by the PMF.

Building repair cost in the non-residential sector was estimated in the same way as for the residential building population. Damage was estimated at building level using 14 vulnerability models developed by GA. Each impacted non-residential building was assigned an appropriate vulnerability model based on its building attributes.

Non-residential building inventory included furniture, fittings, plant and equipment that were not intended for sale in a business. The affected businesses in the study were classified according to the Australian and New Zealand Standard Industrial Classification (ABS, 2006). Each affected business was then catogorised into three major industry types i.e. primary, secondary and tertiary. The primary industry category included agriculture, fishing, forestry and mining. Secondary industry category included manufacturing and construction. The tertiary industry category included retail trade, wholesale trade and other services. Transportation, health care, food, advertising, entertainment, tourism, banking and law are all examples of tertiary sector businesses.

Average inventory loss to an industry category was based on the outcomes of GA's Bundaberg business survey conducted after the January 2013 flood and was inflated to 2016 values. The average loss of inventory to a business in secondary and tertiary categories was estimated by using the business survey to be $35,978 and $32,350, respectively.

The definition of stock included raw materials, work in progress and finished goods that were for sale in a business. In a similar approach to that used to estimate the loss of inventory, the loss of stock in the non-residential sector was estimated for each business by utilising the outcomes of the GA's Bundaberg business survey conducted after the January 2013 flood and was inflated to 2016 values. The average loss of stock in a business in secondary and tertiary categories was estimated to be $2,081 and $18,509, respectively.

The loss of income in the non-residential sector was estimated for three employment categories:

- Owners and managers of incorporated enterprises,
- Owners and managers of unincorporated enterprises, and
- Employees not owning a business.

The first two employment categories represented the loss in proprietary income and third sub-category represented the loss in wage/salary income. Data from a number of sources were collected to estimate the loss of income in the three major industry categories (primary, secondary and tertiary) for each hazard event. The sources included:

- Australian Bureau of Statistics census database (ABS, 2011) accessed through the Census Table Builder to estimate the total number of employed persons and owners of unincorporated and incorporated businesses by Place of Work and to obtain their average weekly income,
- National Regional Profile database (ABS, 2014) to estimate the number of businesses in the three industry sectors in the study area,
- GA's Bundaberg business survey (Canterford, 2016b) to estimate the duration of business interruption for each industry category.

The potential loss of income for each hazard event was calculated as the summation of the product of the number of affected employees and owners in each employment category, the duration of disruption and the average weekly income.

The clean-up cost for the non-residential properties was estimated by using per unit area cost recorded by the Bundaberg Regional Council during the 2013 Bundaberg floods.

The ground floor area affected by each flood event was calculated by overlaying the flood footprint of each event on the building footprints. The unit clean-up costs during the Bundaberg floods to commercial, industrial and institutions were reported to be $1.52, $1.30 and $3.28 per square meter, respectively (Honor, 2017). The total cost of clean-up in each industry category for each hazard event was assessed as the summation of the product of total affected ground floor area and the average clean-up cost per unit area.

The loss of turnover in the non-residential sector was estimated for each business in a similar manner to loss of inventory, by utilising the outcomes of GA's Bundaberg business survey. The average loss of turnover in a business in secondary and tertiary sectors was estimated to be $137,324 and $95,640, respectively. The total potential loss of turnover for each hazard event was calculated as the summation of the product of the number of affected businesses in each industry sector and the average loss of turnover in a business.

Long-term cost

The estimated total losses to the residential and non-residential sector before and after construction of the new levee system are presented in Table 8. The potential loss is the loss without any flood protection system. The conditional loss is the expected loss with a levee system in place considering the likelihood that the levee would fail in the flood. Using these conditional losses, the AAL was calculated for both before and after mitigation. It was found that there is a reduction of $2.91 million in the AAL which reflects the savings made by the investment in mitigation.

TABLE 8: ESTIMATED LOSS BEFORE AND AFTER MITIGATION

ARI (Years)	Potential loss ($M)	Conditional loss - before mitigation ($M)	Conditional loss - after mitigation ($M)	Avergae annual loss – before mitigation ($M)	Avergae annual loss – after mitigation ($M)
100,000	972.2	972.2	972.2	3.95	1.04
1,000	476.5	476.5	476.5		
500	430.2	430.2	43.0		
200	324.8	256.4	0		
100	278.4	111.2	0		
50	232.4	11.9	0		
20	165.8	0.08	0		

Cost benefit analysis

Typically, in Australia, a 7% discount rate has been used within government for investment decisions as it represents the longer term opportunity cost of capital. The present situation of the global COVID pandemic is an exception with lower than usual cost of capital. This is expected to rise again. For climate change studies discount rates as a low as 3.5% have been used (e.g. in the UK) to assess long-term benefits of adaptation as the future climate related impacts and benefits tend to disappear in economic assessments when high discount rates are used (Chigama, 2017).

For the assessment of the Benefit Cost Ratio (BCR) the project life was considered to be 80 years and five annual discount rates (ranging from 3% to 7%) were used to assess the sensitivity of the results to the investment capital cost. The actual investment cost of the project comprised an initial construction and land acquisition cost of $58 million in 2016 dollars.

The ongoing maintenance cost consists of $181,000 annually with an additional $250,000 dollars once every five years for the first twenty years of the project (Fullard, 2016). However, it was assumed that the maintenance cost would be same for both the existing and new levee, and therefore, was not included in the CBA.

The CBA shows that the BCR remained less than 1.0 for the discounted rates of 5% to 7% when the actual project costs were used (see Table 9). However, the BCR improved considerably if the original estimated cost of the project used for decision making was used. This was assessed to be $22 million in 2006 ($28 million in 2016 dollars) by GHD (2006) but was exacerbated later due to increases in the cost of construction and land acquisition (Fullard, 2013). The original estimated cost yielded a BCR greater than 1.0 for all discount rates.

TABLE 9: COST BENEFIT ANALYSES FOR SELECTED DISCOUNT RATES

Cost basis	Total investment (2016 $M)	Avoided losses (2016 $M)					Benefit cost ratio (BCR)				
		3%	4%	5%	6%	7%	3%	4%	5%	6%	7%
Actual cost	58.4	88.0	69.7	57.1	48.1	41.1	1.51	1.19	0.98	0.82	0.71
Estimated cost	27.9	88.0	69.7	57.1	48.1	41.1	3.15	2.49	2.04	1.72	1.48

Avoided losses during June 2016 flood

The results indicated that during the June 2016 flood in Launceston (a 50 year ARI event for the South Esk River based on LCC, 2016) the reconstruction of the levee system resulted in avoiding losses of about $216 million had the pre-existing levees failed. The losses that would be experienced with levee failure would be approximately four times the investment in the new levee system.

Key findings

Key findings of this study are summarised below:

- The losses that would have been experienced during the June 2016 floods should the old levee had failed would be approximately four times the total investment in the new levee system.
- The investment in building the new flood levee system in Launceston was found to be a sound economic decision based on the estimated costs at the time of decision making and improved estimates of benefits from this study.
- Actual benefits of the mitigation works to the community are greater than could be assessed economically and would further support the investment in mitigation.

Invermay Benefit versus Cost Analysis: Aggregated Building Level Mitigation

The suburb of Invermay in the city of Launceston was the first location to be assessed in terms of benefit versus cost of mitigation to individual residential buildings. This study of Invermay utilises some of the material developed for previous utilisation project work, but there are a number of significant differences. The current program of work:

- Assumes that the levee system does not exist.
- Considers only residential buildings and loss due to damage to those buildings. Contents losses and business interruption losses are not considered, nor are rental income losses or the cost of injuries or fatalities.

Launceston building exposure information was pre-existing within the flood research project, having been assembled and used in the Launceston Flood Risk Mitigation Assessment Project (Maqsood et al. 2017b).

The 820 residential buildings within the PMF flood extent for which building level attributes were compiled in the exposure database are included in Figure 27 by the depth of water above floor in the modelled 100 year ARI flood

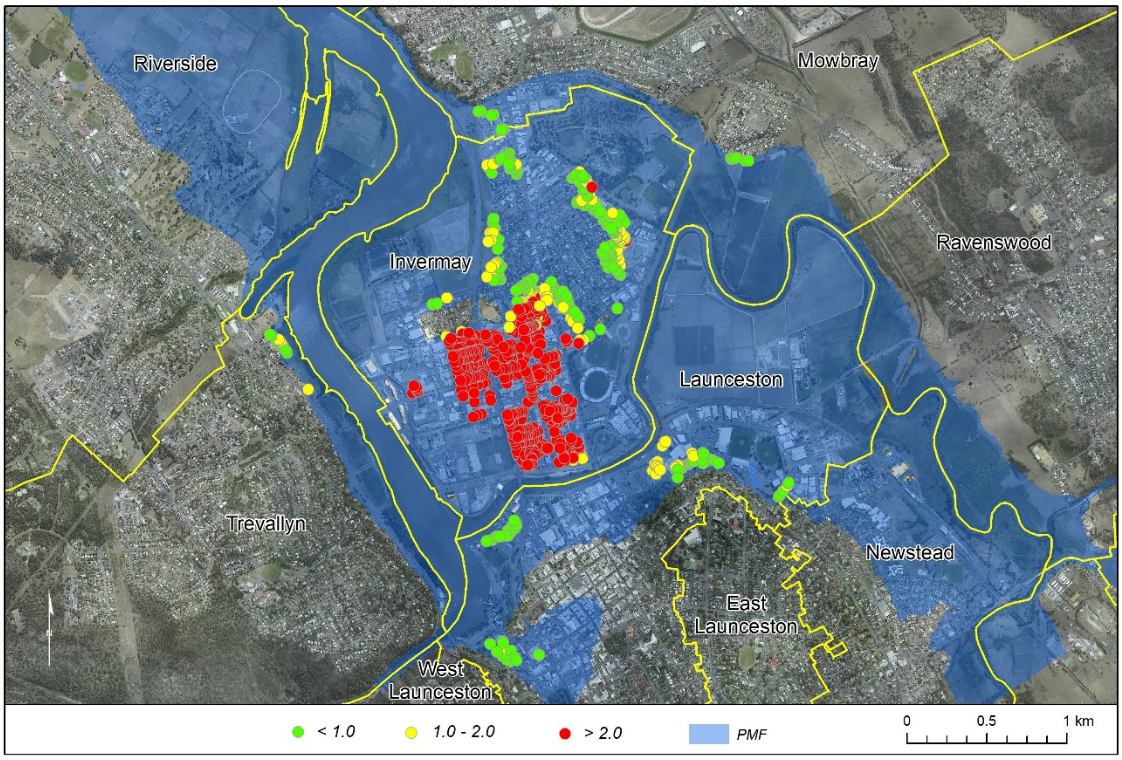

FIGURE 27: RESIDENTIAL BUILDINGS WITHIN PMF EXTENT BY WATER DEPTH OVER FLOOR IN 100 YEAR ARI EVENT

Application of Mitigation Options through the Floodplain

Assuming no existing flood protection works in Launceston, a number of options related to mitigation were explored through this work. Firstly, not all mitigation options are appropriate for all the considered residential building types. Consideration was also given to the uptake of mitigation options within the floodplain. The 'ideal' mitigation results are based on every building for which a mitigation option is appropriate being virtually retrofitted (i.e. 100% of the applicable building stock have been modified to reduce their vulnerability). This is not a realistic outcome so a number of other scenarios with lower percentages of retrofit uptake have also been modelled. Three retrofit zones were defined based on their hazard related to the 100 year ARI. The extents of the zones are shown in Figure 28 with definitions as follows:

- Retrofit Zone 1 Red: High risk, 488 properties, inundation greater than 2m in the 100 year ARI event
- Retrofit Zone 2 Yellow: Medium risk, 111 properties, inundation between 1m and 2m in the 100 year ARI event
- Retrofit Zone 3 Green: Low risk, 221 properties, inundation less than 1m in the 100 year ARI event.

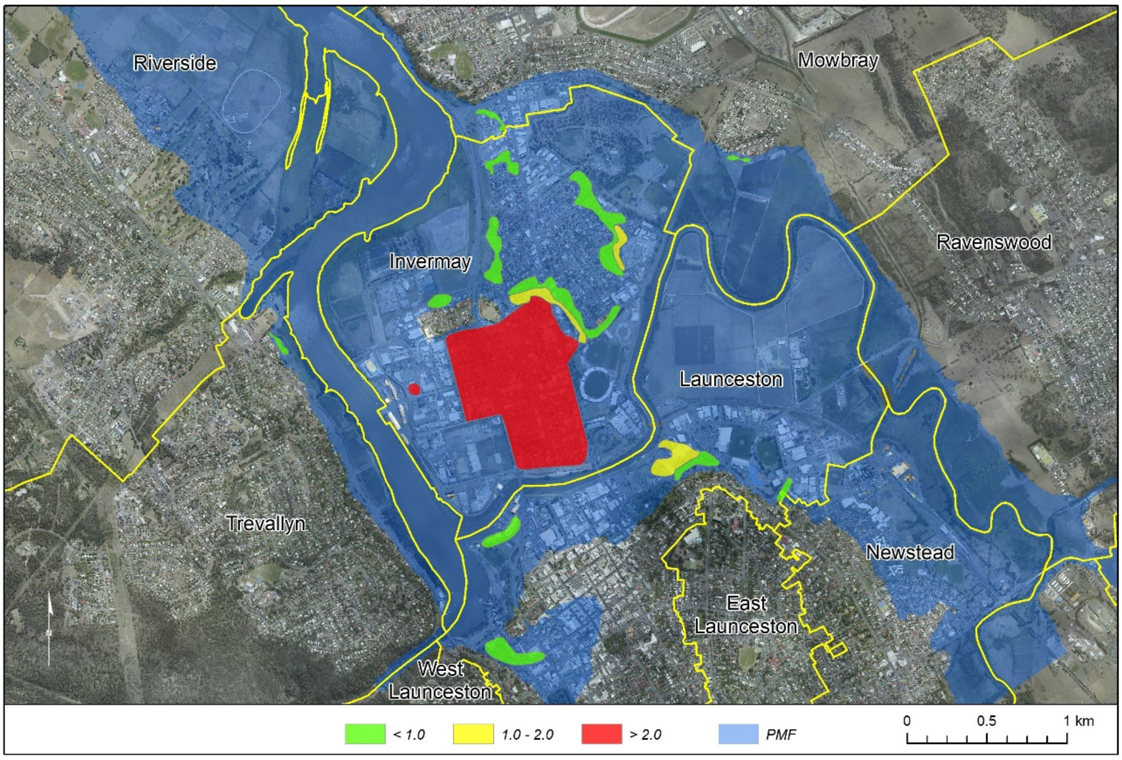

FIGURE 28: EXTENTS OF RETROFIT ZONES

The assumed retrofit percentages for applicable buildings by zone are shown in Table 10. They were chosen to try and reflect the most practical measures to be taken in the different zones. The temporary barrier system was chosen to provide protection as displayed in Figure 29. The barrier placement coincides with sealed roadways that it can be placed upon.

TABLE 10: SUMMARY OF ASSUMED MITIGATION UPTAKE BY ZONE

Mitigation Option	Assumed Mitigation Uptake by Zone (applicable wall types only)		
	Zone 1	Zone 2	Zone 3
House raising (3m)	30%	-	-
House raising (2m)	-	20%	-
Relocation	10%	-	-
Dry floodproofing	-	-	10%
Wet floodproofing - Existing	10%	20%	30%
Wet floodproofing - Reno	10%	20%	30%
Barriers	100%	-	-

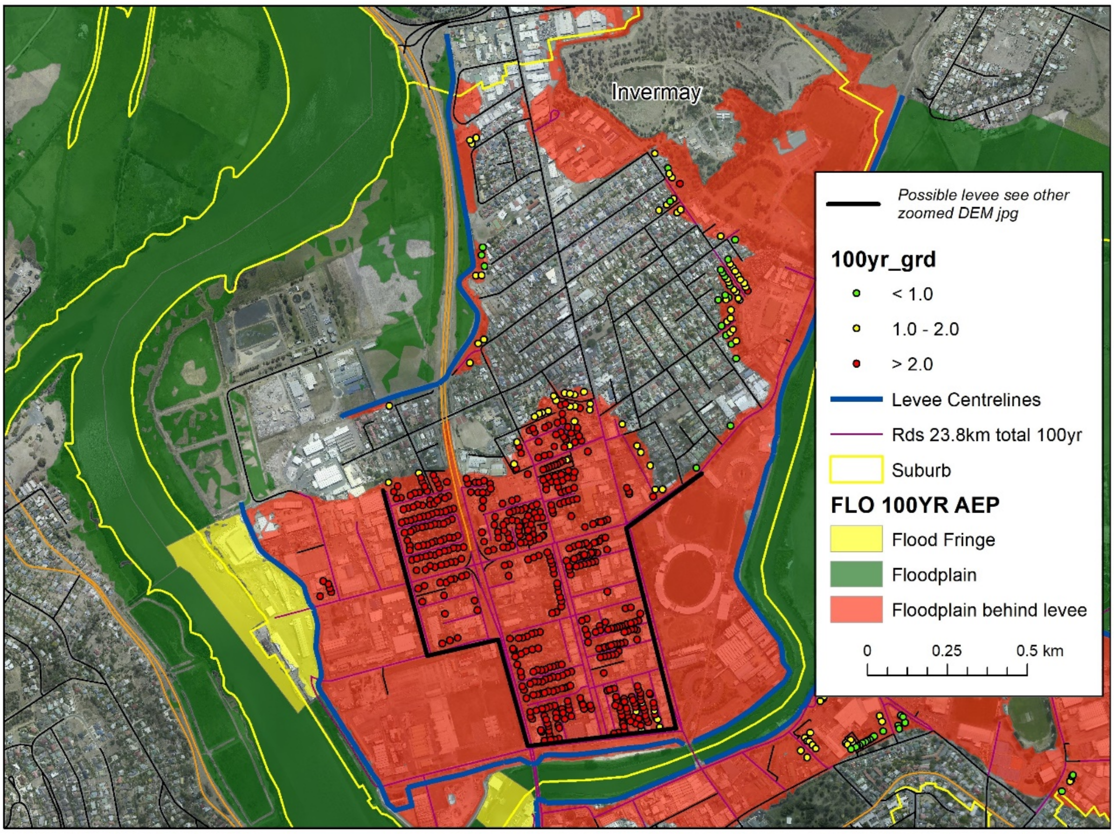

FIGURE 29: ASSUMED PLACEMENT OF TEMPORARY BARRIER SYSTEM

Results

Risk can be measured as the aggregated annualised dollar loss (AAL) due to building damage, essential service disruption, injury/fatality, community disruption, business inventory loss or economic activity disruption caused by hazard events over the full range of event likelihoods. For this study, risk has been assessed in terms of economic loss (or costs) from residential building damage only.

The benefit due to mitigation is measured in the reduction in AAL. Investment costs are calculated as unit mitigation costs multiplied by the number of properties mitigated. The barriers are an exception to this with the following assumptions made in assessing the cost of barriers in addition to the initial cost of purchase:

- A storage cost of $25k per year is included
- The cost of installation/removal has been applied 14 times
- The barriers will need replacement after 40 years.

For the assessment of the benefit versus cost ratio the project life was considered to be 80 years and five annual discount rates (3% to 7%) were used to assess the sensitivity of the results to the investment capital cost. Investment costs, avoided losses and benefit cost ratios are summarised in Table 11 (ideal case, 100% application), Table 12 (Zone 1 mitigation options), Table 13 (Zone 2 mitigation options), and Table 14 (Zone 3 mitigation options).

TABLE 11: AVOIDED LOSSES AND BENEFIT VERSUS COST RATIO FOR 100% APPLICATION IN ALL ZONES

All Applicable Locations	Investment Cost ($M)	Avoided Losses ($M)					Benefit Cost Ratio (BCR)				
		3%	4%	5%	6%	7%	3%	4%	5%	6%	7%
House raising (3m)	45.83	142.55	112.88	92.50	77.92	67.13	3.11	2.46	2.02	1.70	1.46
House raising (2m)	45.83	129.86	102.84	84.26	70.99	61.15	2.83	2.24	1.84	1.55	1.33
Relocation	33.99	147.38	116.71	95.63	80.56	69.40	4.34	3.43	2.81	2.37	2.04
Dry floodproofing	29.02	22.35	17.70	14.50	12.22	10.52	0.77	0.61	0.50	0.42	0.36
Wet floodproofing - Existing	9.25	34.43	27.26	22.34	18.82	16.21	3.72	2.95	2.42	2.03	1.75
Wet floodproofing - Reno	10.14	52.55	41.61	34.10	28.73	24.75	5.18	4.10	3.36	2.83	2.44
Barriers	10.68	76.11	60.27	49.38	41.60	35.84	8.23	7.11	6.20	5.47	4.86

TABLE 12: AVOIDED LOSSES AND BENEFIT VERSUS COST RATIO FOR ZONE 1

Zone 1	Investment Cost ($M)	Avoided Losses ($M)					Benefit Cost Ratio (BCR)				
		3%	4%	5%	6%	7%	3%	4%	5%	6%	7%
House raising (3m)	8.68	33.64	26.64	21.83	18.39	15.84	3.88	3.07	2.51	2.12	1.83
Relocation	2.15	10.84	8.59	7.04	5.93	5.11	5.05	4.00	3.28	2.76	2.38
Wet floodproofing - Existing	1.70	8.37	6.62	5.43	4.57	3.94	4.92	3.89	3.19	2.69	2.32
Wet floodproofing - Reno	1.80	12.35	9.78	8.01	6.75	5.82	6.85	5.43	4.45	3.75	3.23
Barriers	6.16	50.44	39.94	32.73	27.57	23.75	8.18	7.10	6.22	5.50	4.90

TABLE 13: AVOIDED LOSSES AND BENEFIT VERSUS COST RATIO FOR ZONE 2

Credible Zone 2	Investment Cost ($M)	Avoided Losses ($M)					Benefit Cost Ratio (BCR)				
		3%	4%	5%	6%	7%	3%	4%	5%	6%	7%
House raising (2m)	1.09	3.14	2.49	2.04	1.72	1.48	2.87	2.27	1.86	1.57	1.35
Wet floodproofing - Existing	0.28	1.15	0.91	0.74	0.63	0.54	4.03	3.19	2.62	2.20	1.90
Wet floodproofing - Reno	0.35	1.60	1.27	1.04	0.87	0.75	4.54	3.60	2.95	2.48	2.14

TABLE 14: AVOIDED LOSSES AND BENEFIT VERSUS COST RATIO FOR ZONE 3

Credible Zone 3	Investment Cost ($M)	Avoided Losses ($M)					Benefit Cost Ratio (BCR)				
		3%	4%	5%	6%	7%	3%	4%	5%	6%	7%
Dry floodproofing	1.74	1.96	1.55	1.27	1.07	0.92	1.13	0.90	0.73	0.62	0.53
Wet floodproofing - Existing	0.24	0.45	0.36	0.29	0.25	0.21	1.85	1.46	1.20	1.01	0.78
Wet floodproofing - Reno	0.29	0.60	0.48	0.39	0.33	0.28	2.09	1.65	1.35	1.14	0.98

For this study of Launceston without existing flood protection levees, nearly all of the mitigation options analysed yield a benefit versus cost ratio of greater than 1.0, signifying a good investment decision. Exceptions (BCR less than 1.0) occur in Zone 3 for dry floodproofing (4%-7% discount) and wet floodproofing (7% discount). The use of temporary barriers in the high hazard Zone 1 is the most cost-effective of all the measures with a BCR ranging between 5 and 8 depending on the discount rate used.

Full reporting on the Invermay analysis has been prepared by Maqsood et al. (2020).

Benefit versus Cost Analysis: Individual Building Level Mitigation

The final benefit versus cost analyses were based on fictional individual buildings in three catchments. The buildings represented the five types chosen as the focus of this work and described in the section on 'Costing of mitigation strategies and development of flood vulnerability models for mitigated building types' and Table 3. The selected catchments were chosen based on their characteristics as described below.

Catchment type definition

The project team investigated ways of defining catchment behavior in an attempt to cover as many situations as possible (i.e. catchment behavior and building stock variation) in the benefit versus cost analyses. Through a collaboration agreement between IAG and Geoscience Australia the team has been able to access flood studies held in IAG's database.

The method the team has used is to take flood depths for a range of Average Recurrence Intervals (ARIs) for all residential buildings within the 100 year ARI flood extent map and fit a curve through the points. The slope of the curves from a number of flood studies can be used to characterise catchments into three typical types (low, medium, high) based on selected definition/criteria.

As an example Figure 30 shows results from a number of different catchments with average flood depth plotted against ARI. The 'steepness' of the regressed line will be used in defining catchments into three types as discussed in the previous point. In turn, this relativity in flood depth versus ARI will feed into the economic evaluation for each retrofit measure if implemented for each catchment type.

Following a scan of available flood information the three catchments chosen were those of Launceston, Brisbane and the Lower Hunter. The change in flood depth with ARI for these three examples is shown in Figure 31.

Benefit versus cost ratio assessment

Because the benefit versus cost analysis was performed on fictional buildings without a specific location in each of the floodplains a number of floor heights were modelled for each building type and floodplain combination. The floor heights used in the study for each floodplain are presented in Table 15.

The BCR in this instance was based only on the building structure itself: contents, loss of rental and other potentially significant costs were not assessed. Each of the five building types were assessed in each floodplain assuming the four floor heights provided in Table 15.

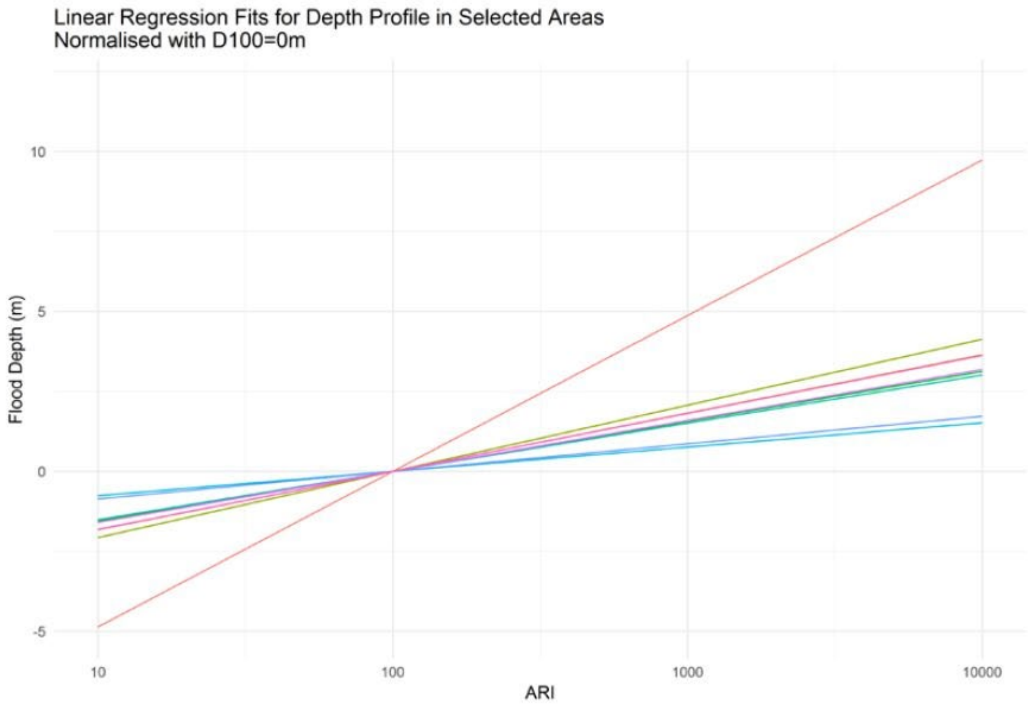

FIGURE 30: EXAMPLES OF CATCHMENT 'STEEPNESS' USING IAG FLOOD DATABASE

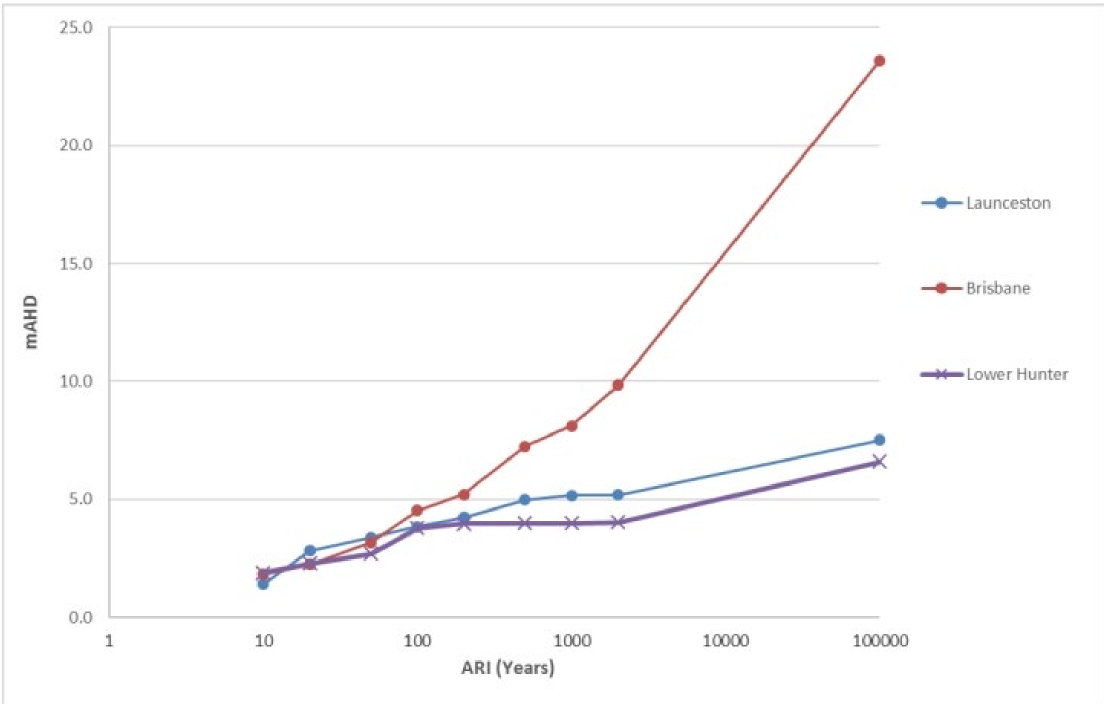

FIGURE 31: FLOOD DEPTH VERSUS ARI FOR THREE CATCHMENTS

TABLE 15: ASSUMED CASE STUDY FLOOR HEIGHTS (AHD) FOR THE THREE STUDY AREAS

Case	Launceston	Brisbane	Hunter
Case 1	1.1m	2.8m	2.5m
Case 2	1.6m	3.8m	3.0m
Case 3	2.1m	4.8m	3.5m
Case 4	2.6m	5.8m	4.0m

Each of the five building types was assessed to determine its AAL in 'original' state and then also for each of the appropriate mitigation measures for the particular building type. The original and modified curves provided earlier in the report were used in this analysis. The cost of mitigation options was also provided earlier in the report in Table 4. Barriers were assumed to protect only individual houses. It is likely that barriers rarely protect a single house and the benefit may be larger if the barrier costs are spread across a number of properties. Discount rates from 3% to 7% were considered in assessing the BCR.

Benefit versus cost ratio results are shown for the five building types and three catchments from Figure 32 to Figure 38. Tabular results are provided in Appendix F. Abbreviations used in the figures for the mitigation strategies are as follows:

- WFP-EXS Wet floodproofing (Existing Structure)
- WFP-RNV Wet floodproofing (during renovation)
- ELE Elevation
- TEMP900 Temporary barriers (900mm high)
- TEMP1200 Temporary barriers (1200mm high)
- PERM1000 Permanent barrier (1000mm high)

As expected the cost-effectiveness of mitigation options depends on the catchment and building characteristics. For building type CRC1, elevation is the most appropriate and cost-effective option. For building types CRC2, CRC3 and CRC4, elevation is typically the most cost-effective option, however, with a lower benefit cost ratio than for CRC1. For building type CRC5, the use of temporary barriers and wet floodproofing are typically the most cost effective options.

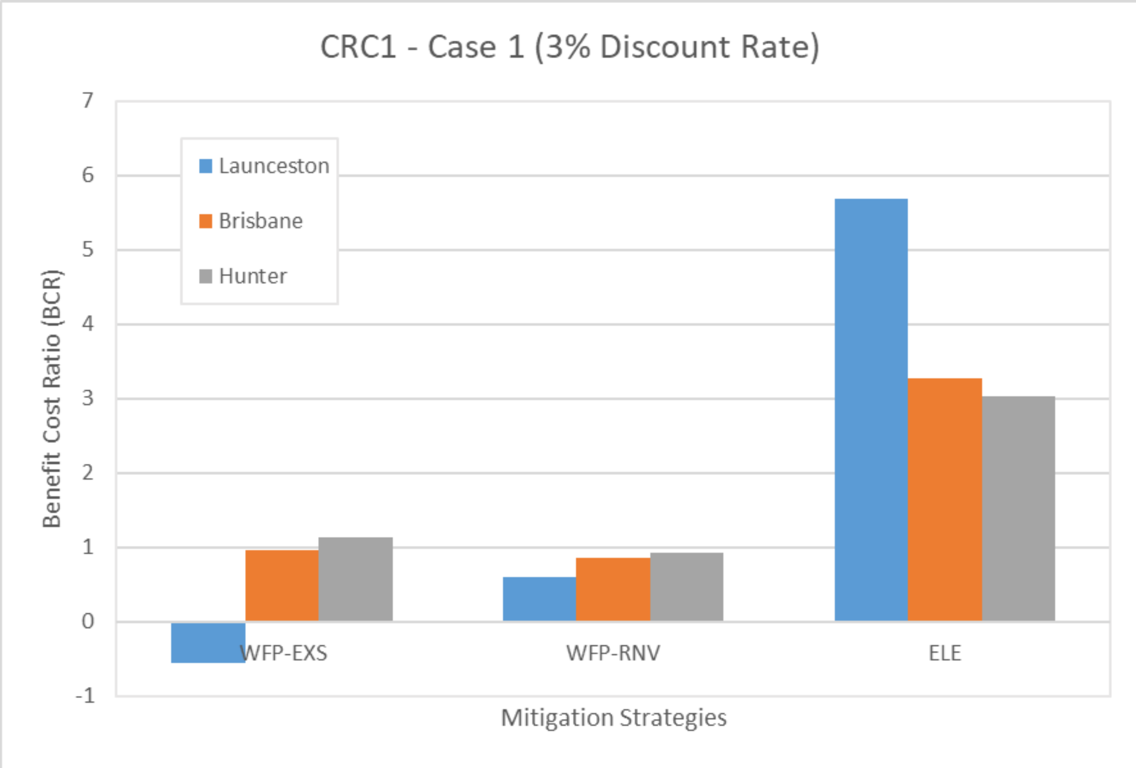

FIGURE 33: BENEFIT VERSUS COST RATIOS FOR BUILLDING TYPE CRC1, CASE 1 AND 3% DISCOUNT RATE

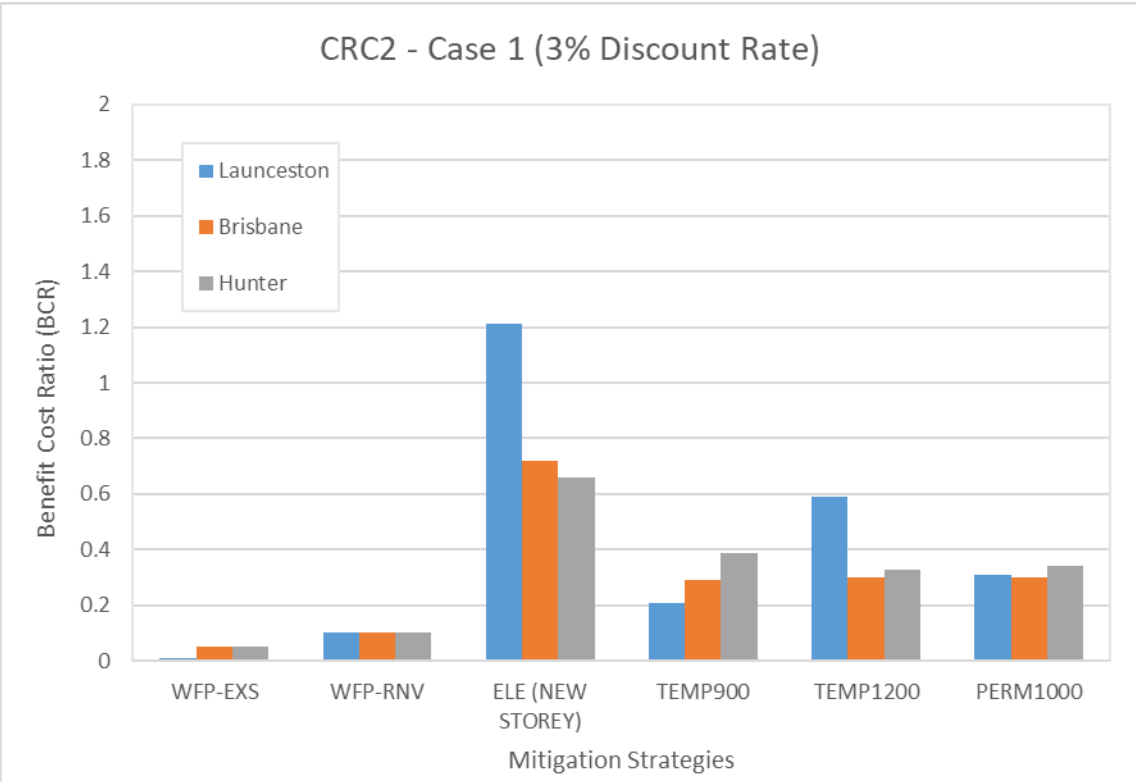

FIGURE 32: BENEFIT VERSUS COST RATIOS FOR BUILLDING TYPE CRC3, CASE 1 AND 3% DISCOUNT RATE

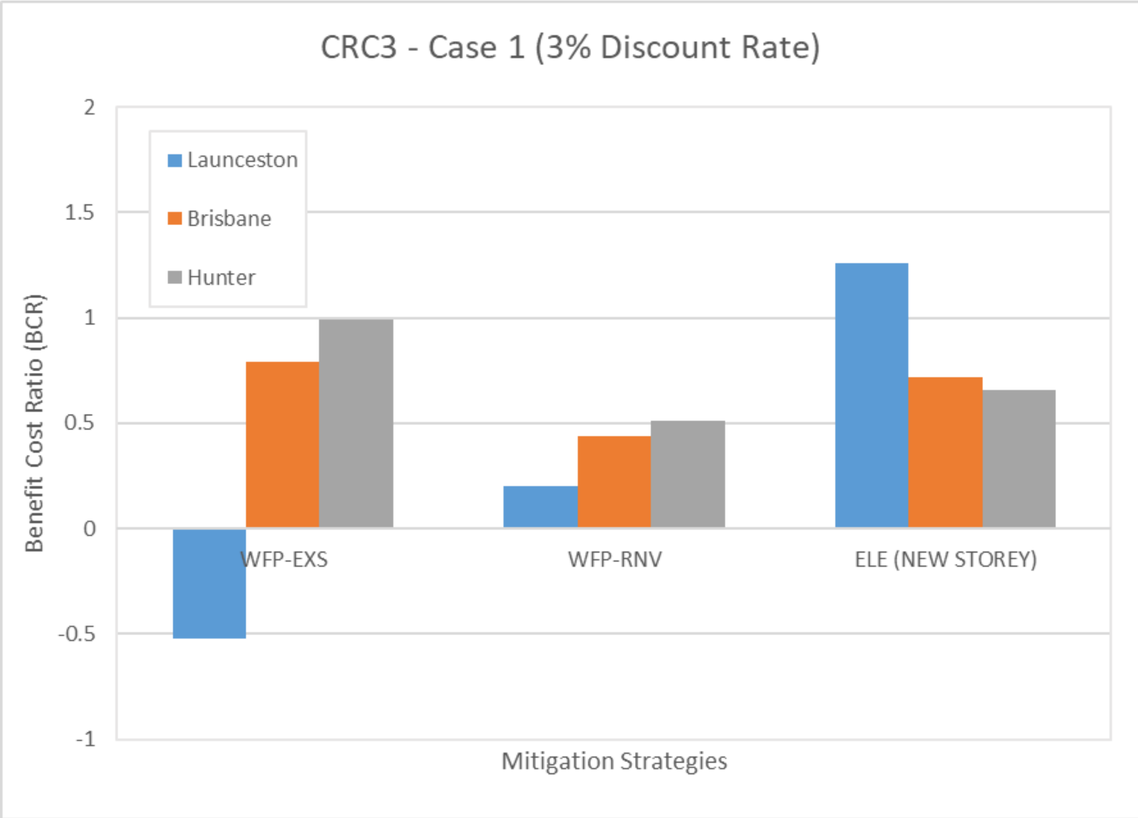

FIGURE 35: BENEFIT VERSUS COST RATIOS FOR BUILLDING TYPE CRC2, CASE 1 AND 3% DISCOUNT RATE

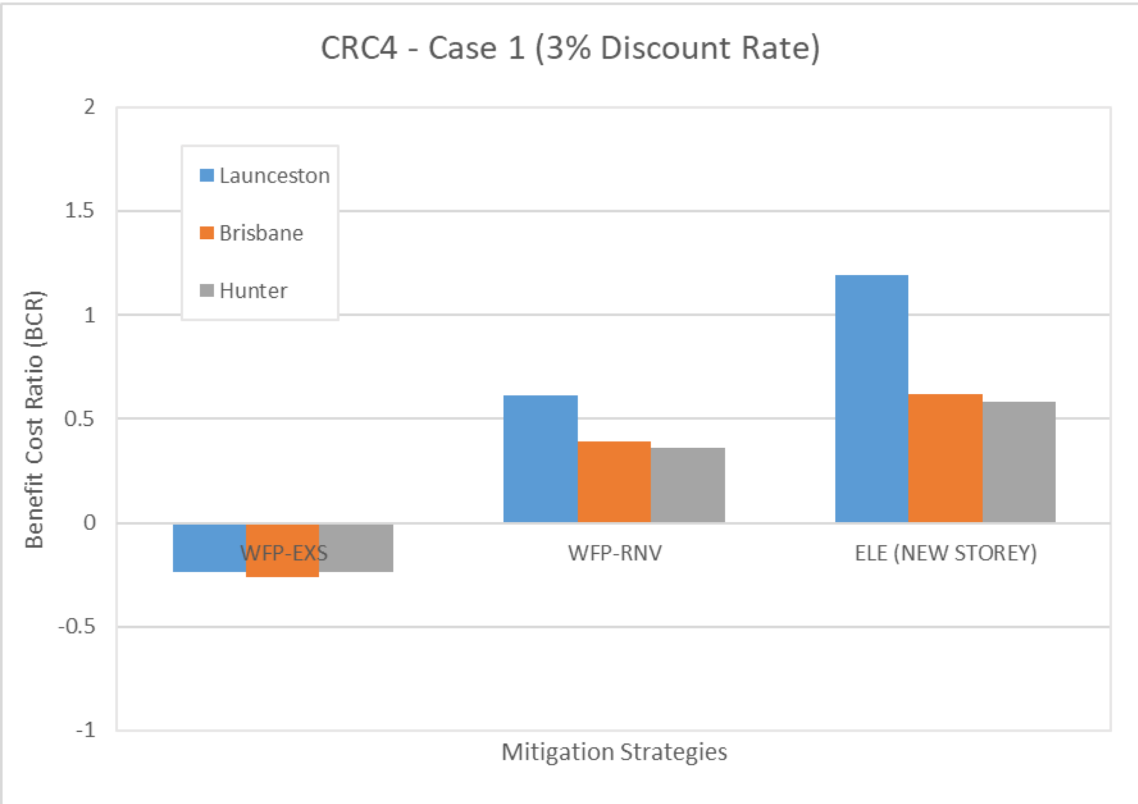

FIGURE 34: BENEFIT VERSUS COST RATIOS FOR BUILLDING TYPE CRC4, CASE 1 AND 3% DISCOUNT RATE

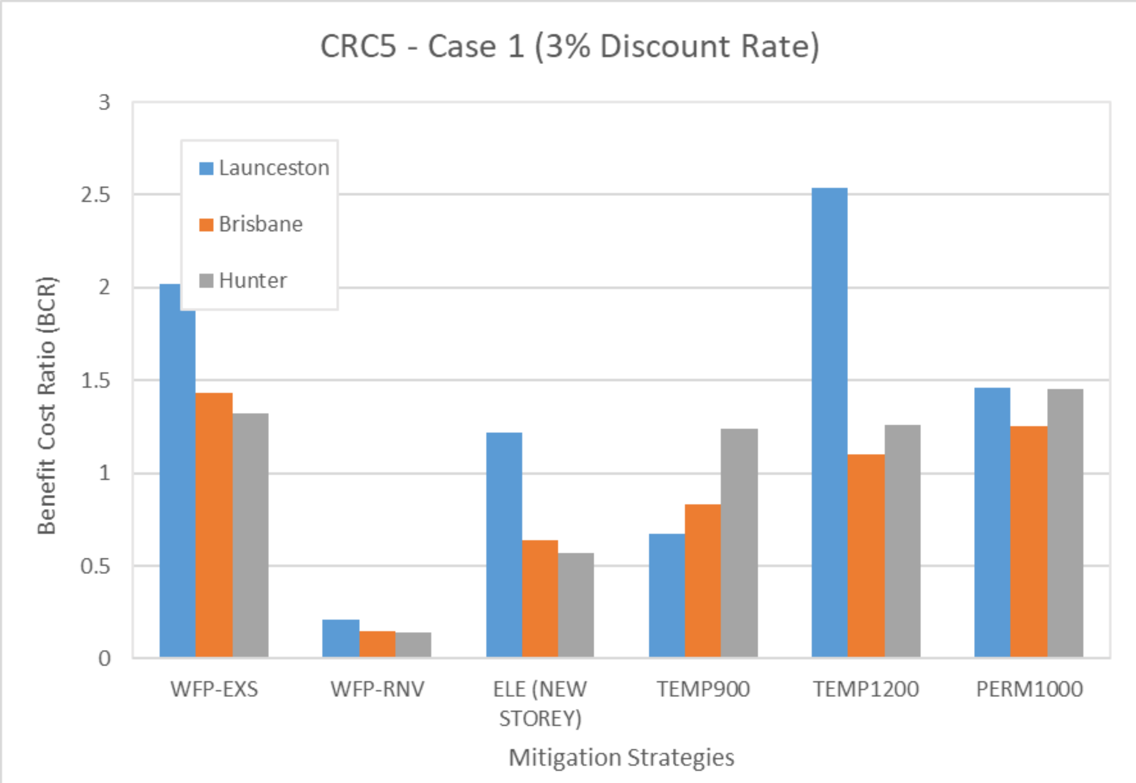

FIGURE 36: BENEFIT VERSUS COST RATIOS FOR BUILLDING TYPE CRC5, CASE 1 AND 3% DISCOUNT RATE

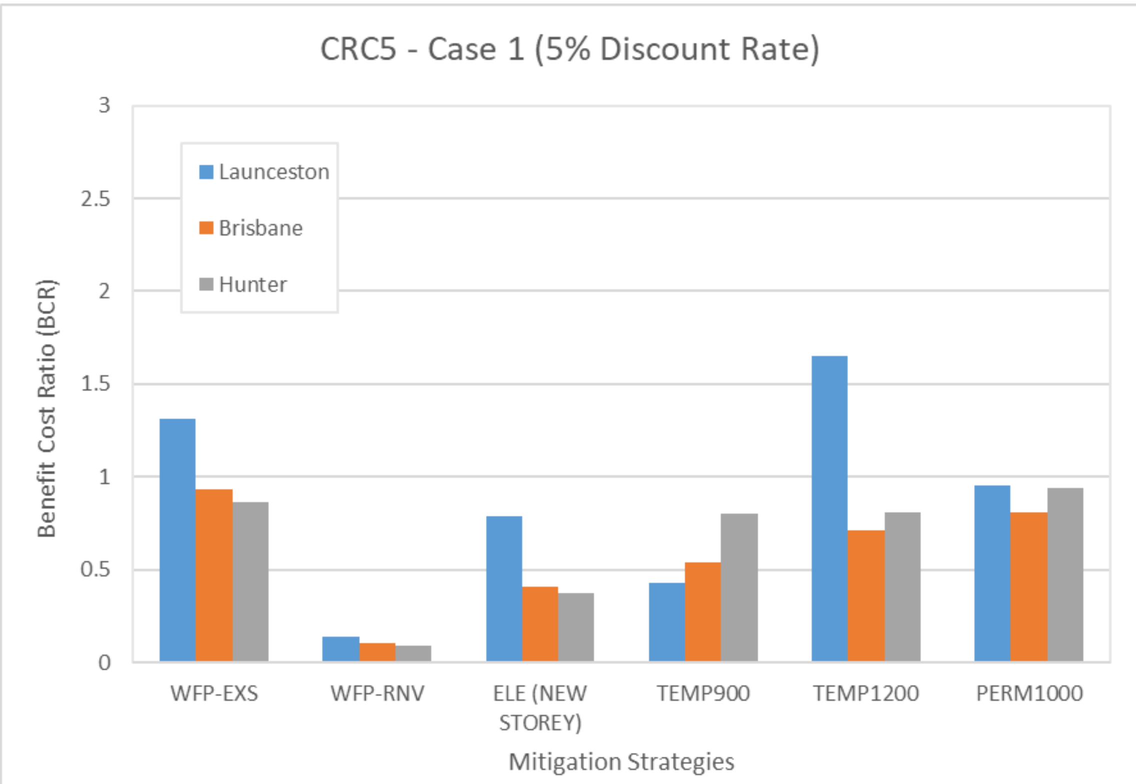

FIGURE 37: BENEFIT VERSUS COST RATIOS FOR BUILLDING TYPE CRC5, CASE 1 AND 5% DISCOUNT RATE

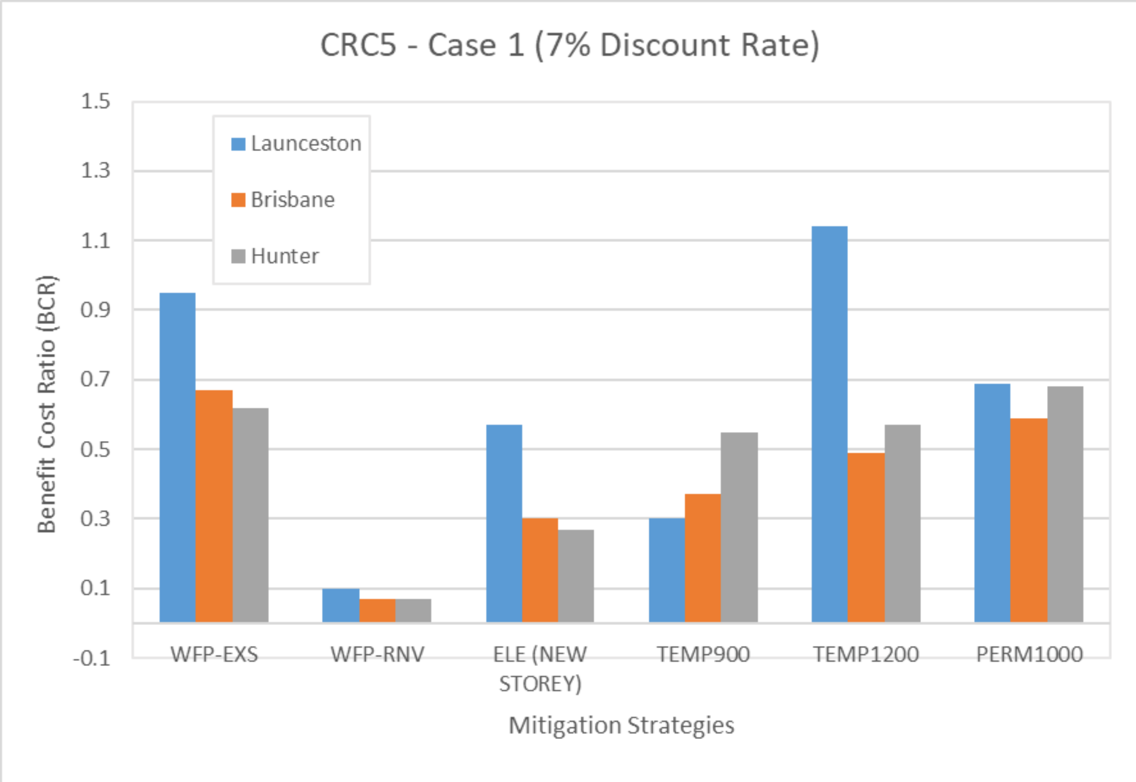

FIGURE 38: BENEFIT VERSUS COST RATIOS FOR BUILLDING TYPE CRC5, CASE 1 AND 7% DISCOUNT RATE

FINDINGS

This report presents the cost versus benefit analyses of mitigating five Australian house types against riverine flooding. Mitigation efforts were assessed at three scales: community level, building level (aggregated), and building level (individual). Key milestones and their outcomes/findings are described in the following paragraphs.

A building classification schema divided each building into the sub-elements of foundations, bottom floor, upper floors (if any) and roof to describe its vulnerability. This approach permitted assessments of the vulnerability of structures with different usages and/or construction materials used in different floors, and also assessments of the vulnerability of tall structures with basements where only basements and/or bottom floors are expected to be inundated. The schema classified each storey type based on six attributes: construction period, fit-out quality, storey height, bottom floor, internal wall material and external wall material.

A literature review of mitigation strategies developed nationally and internationally was undertaken to evaluate strategies that would suit Australian building types and typical catchment behaviours. The review resulted in five mitigation strategies deemed appropriate for Australian residential buildings: elevation, relocation, dry floodproofing, wet floodproofing, and flood barriers. These categories were those studied in the remainder of the research project.

The strength and durability implications of the immersion of key structural elements and building components in conditions of slow water rise were examined through a testing program. The objective of the testing was to identify whether the selected components remain serviceable following inundation and subsequent drying or whether replacement was required. The experimental program examined the bond strength of floor and wall ceramic tiles to their substrate, the racking strength of two types of sheet wall bracing, and the bending and shear strength of engineered timber joists. In most cases the specimens showed only minor reductions in capacity after saturation. The engineered timber joists were an exception and had a significant (46%) reduction in load carrying capacity when tested in the wet state.

Costing modules were developed by quantity surveying specialists to estimate the cost of implementing all appropriate mitigation strategies for the five storey types chosen for analysis. New vulnerability curves were developed for the five building selections under all appropriate mitigation options. The curves are stage-damage curves which relate the height of water above the floor to a dollar loss for that building type. Mitigted curves will generally be lower to some degree than the original curves for that storey type (i.e. less damage for the same depth of water).

The original and mitigated curves were used in cost versus benefit analyses at three levels of resolution. At a community level Launceston was studied to assess the cost-effectiveness of a levee system constructed in the 2010s. The study utilised detailed building exposure information and assessed residential and non-residential building damage and a range of other losses, including to inventory, loss of rental income, loss of business income and the cost of fatalities. Findings included the losses that would have been experienced during the June 2016 floods should the old levee had failed. These were found to be approximately four times the total investment in the new levee system. The investment in building the new flood levee system in Launceston was found to be a sound economic decision based on the estimated costs at the time of decision making and improved estimates of the long term benefits provided by this study.

The suburb of Invermay in the city of Launceston was the first location to be assessed in terms of benefit versus cost of mitigation to individual residential buildings. This study of Invermay utilised some of the material developed for the Launceston study, but there are a number of significant differences. The Invermay study assumes that the levee system does not exist and also considers only residential buildings and loss due to damage to those buildings. The study assumed the existing levee protection was not present and examined a number of levels of mitigation 'take-up'. This work indicated that the majority of mitigation options yielded benefit cost ratios above 1.0, signifying a cost-effective investment. The key exception was dry floodproofing in one of the hazard zones. The use of temporary barriers in the high hazard zone provided the highest benefit versus cost ratios.

Finally individual buildings were assessed under three catchment conditions and for a range of floor heights in the flood zone. For building type CRC1 (timber frame construction with a raised floor), elevation is the most appropriate and cost-effective option. For building types CRC2 (Victorian terrace with a raised floor), CRC3 (cavity masonry with a raised floor) and CRC 4 (brick veneer with a raised floor), elevation is typically the most cost-effective option, however, with a lower benefit cost ratio than for CRC1. For building type CRC5 (brick veneer with slab-on-grade), the use of temporary barriers and wet floodproofing are typically the most cost effective options.

UTILISATION AND IMPACT

SUMMARY

In addition to the core work program of this project, two utilisation projects through the CRC have also been undertaken. The costs and benefits of flood risk mitigation in Launceston was a study commissioned to examine the effectiveness of a flood levee system upgrade that commenced in 2010 and was nominally completed in 2014, however, a section of the levee was completed just prior to floods in 2016. The study was completed in 2017.

A further utilisation project commenced in 2018 with an aim of translating vulnerability information (existing and mitigated) developed by Geoscience Australia (GA) into practical guidance for flood risk managers undertaking studies under the floodplain-specific management process as outlined in AEM Handbook 7 (AIDR 2017). The utilisation projects are described further in the following sections.

COSTS AND BENEFITS OF FLOOD RISK MITIGATION IN LAUNCESTON

Output description

This utilisation project reviewed the costs and benefits of flood mitigation work (upgraded levees) in Launceston, Tasmania. The upgrade of the levee system began in 2010 and was nominally completed in 2014. Severe flooding in Launceston in 2016 provided an opportunity to assess the cost and benefit of the levee system.

The flood mitigation through the improved levee system did not extend to the suburb of Newstead in the east of Launceston and a new levee was proposed to protect these properties from future floods. As part of the utilisation activity the project team also conducted a cost benefit analysis of the proposed flood levee in Newstead. This piece of work also afforded the opportunity to include intangible losses due to mental health, social disruption, amenity, safety and a number of other intangible mechanisms. The intangible losses were developed in conjunction with researchers at the University of Western Australia working on a CRC project (CRC, 2021c).

Extent of use

- This work was undertaken with a number of end-user stakeholders who have been able to utilise the outputs from this activity:
    - City of Launceston
    - Launceston Flood Authority
    - Tasmanian Department of Premier and Cabinet
    - Northern Midlands Council
    - Tasmanian State Emergency Service

- The outcomes of the utilisation project were also included in a submission to the Independent Review into the Tasmanian Floods of June and July 2016 (Blake, H. 2017).

Utilisation potential

- There is potential for further utilisation related to this work. The flood hazard for Launceston has been reassessed following the 2016 floods with the hazard reported to have increased (Leister, J. 2019). Climate change has also been considered and found to siginificantly exacerbate future flood hazard. A logical extension to this work would be to reassess the cost versus benefit analysis using the updated hazard and the project team plans to pursue this.
- This activity also featured the project team incorporating intangible costs in the estimation of losses for the first time. The inclusion of these types of costs helps in creating a more holistic picture of impact due to an event. There is ongoing potential for the inclusion of these types of costs in project activities, particularly in assessing the effectiveness of mitigation measures.

Utilisation impact

- The outcomes of the cost benefit analysis into the Launceston levee system were quoted and referenced in the report on the independent review into the floods (Blake, H. 2017).

Utilisation and impact evidence

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FLOOD DAMAGE MODELS FOR FLOODPLAIN MANAGEMENT

Output description

The aim of this utilisation project was to provide advice on assessing flood impact and risk to floodplain managers and others who may not have access to detailed building exposure information. It involved developing and testing a number of resolution options (from asset specific vulnerability assessments to more generalised methods) in a series of case studies.

Key activities in this project included:

- the development of a typology for grouping community exposure;
- the selection of case study communities;

- the collection of flood and building exposure data for those communities, and enhancement of the building exposure where required; and
- the development of generalised curves.

Three workshops were convened through the project: at commencement, mid-project and at the conclusion. Following the mid-project workshop the use of land-use planning zones as the aggregation level for creating generalised functions was adopted. This data was gathered in Murwillumbah, Tweed Heads and Launceston and all buildings in those locations assigned the appropriate land-use attribution. With this information collated, work was undertaken in developing a new suite of generalised vulnerability curves at this resolution. The newly created generalised curves were then used in assessing flood damage for the study areas described above and the full range of flood likelihoods. Where the data was sufficient, curves were developed using half of the dataset and checked against the other half. Comparisons were undertaken between the generalised and detailed curve outputs. Full reporting on the utilisation project was provided by Dale et al. (2021).

Extent of use

- The project has only just completed with full dissemination of the final deliverables to come, but the stakeholder group includes:
    - National Flood Risk Advisory Group (NFRAG)
    - Floodplain Management Australia (FMA)
    - Australian Institute for Disaster Resilience (AIDR)
    - Local Government
    - Insurance Industry (Insurance Australia Group and the Insurance Council of Australia)
    - Consulting Industry

Utilisation potential

- There is broad potential for the use of generalised curves by those who do not have access to detailed building exposure information. Users could include floodplain managers, flood consultants, state emergency services, and impact modellers.
- The curves may assist in facilitiating national-scale flood impact forecasting due to the removed need for detailed exposure information.
- The curves would allow consistent comparisons to be made across jurisdictions where exposure information may otherwise be inconsistent, benefitting decision makers in comparing flood impact and risk.
- The publication of the finalised curves and use instructions through AIDR will allow for widespread dissemination and access.

Utilisation impact

- The broad stakeholder group interested in the proposed project outputs suggests that, if fit for purpose, the impact should be widespread, particularly with dissemination through AIDR.

Utilisation and impact evidence

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CONCLUSION

This report presents a summary of outcomes from the CRC project, *Cost-effective mitigation strategy development for flood prone buildings*. The project focusses on the development of an evidence base for decision-makers (including home owners) on the cost effectiveness of a variety of mitigation measures on Australian residential buildings.

Analyses were conducted on community level mitigation through levees (Launceston), of the application of individual building retrofit with a community outcome focus (Invermay), and of individual buildings in three different catchment types (Launceston, Brisbane, Lower Hunter).

Launceston was studied to assess the cost-effectiveness of a levee system constructed between 2010 and 2014. The study assessed both residential and non-residential building damage and a range of other losses, including inventory, related loss of rental income, loss of business income and the cost of fatalities. The investment in building the new flood levee system in Launceston was found to be a sound economic decision based on the estimated costs at the time of decision making and improved estimates of benefits from this study.

The Invermay study assumed no existing flood protection works in Launceston and explored a number of mitigation options at the building level. Consideration was given to the uptake of mitigation options within the floodplain with an 'ideal' situation based on every building for which a mitigation option is appropriate being virtually retrofitted. This is not a realistic outcome so a number of other scenarios with lower percentages of retrofit uptake have also been modelled. The majority of mitigation options analysed yielded benefit versus cost ratios of greater than 1.0, indicating a good investment decision. Exceptions included some cases of both dry and wet floodproofing. The use of temporary barriers in the high hazard zone was the most cost-effective of all the measures studied (costs were shared across the protected properties in this instance).

The analyses of individual buildings across a variety of catchment characteristics resulted in mixed outcomes in terms of benefit versus cost. For the light framed building type, elevation is the most appropriate and cost-effective option. For the Victorian Terrace, the cavity masonry and brick veneer structures with a raised timber floor elevation was also typically the most cost-effective option (although not as effective as for the light frame structure). For a slab-on-grade brick veneer structure the use of temporary barriers and wet floodproofing were typically the most cost effective options.

NEXT STEPS

Much of the work described here assesses loss only in terms of the building structure itself. The inclusion of residential contents models in the individual building assessments is a logical next step and would provide more benefit for the mitigation efforts. Similarly, the inclusion of other benefits in terms of household disruption would also provide a more accurate picture of the costs avoided through mitigation.

Feedback has already been received from the NFRAG group regarding the potential inclusion of a modern two storey brick veneer home as a gap (mitigated and unmitigated), so this is also a consideration as a next step.

There exists an opportunity to revist the study on the Launceston levee system given the reference to a newly calculated higher level of hazard.

Similar work could be undertaken with other local government stakeholders to provide better information on the most effective mitigation measures for their particular flood plain.

Further engagement with the insurance sector will also be an important follow-up to this research, given their ability to incentivise retrofit options to householders. This engagement would also provide a valuable opportunity to validate and/or refine current models. It would also enable the improved vulnerability knowledge to be translated better into the insurance sector where policies cover other costs not captured by this research.

The generalised vulnerability model approach could be extended and refined for other community typologies. This would support nationally consistent flood risk assessments. Further, the translation of these models into a flood impact forecasting capability could be explored.

There is opportunity to utilise the parallel CRC research by the University of Western Australia on intangible values in broader flood risk studies and the assessment of mitigation effectiveness. The Newstead study as part of the Launceston work in this research was an initial demonstrator of this.

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TEAM MEMBERS

RESEARCH TEAM

Dr Ken Dale

Dr Dale is a structural engineer at Geoscience Australia who obtained his Bachelor Degree (1994) and PhD (2001) at Monash University. Ken undertook Post-Doctoral research in Japan related to the earthquake behaviour of steel beam-to-column connections (2001-2003) before joining Geoscience Australia in 2003. Research interests include the behaviour of structures and other infrastructure under extreme loads (blast, flood, tsunami, and earthquake). Research in the flood area has included modifying damage curves that incorporate flood height and velocity to suit Australian construction, and the development of stage-damage curves for a small suite of residential structures. Flood experience also includes leading teams on post-event damage surveys in Melbourne (2004) and Brisbane (2011). He is a Member of Engineers Australia and IABSE.

Dr Tariq Maqsood

Dr Maqsood is a Senior Lecturer at RMIT University. Before joining the university in 2018 Dr Maqsood was a structural engineer at Geoscience Australia. He is a member of Civil College of Engineers Australia and also a member of the Australian Earthquake Engineering Society (AEES). During the last 15 years Dr Maqsood has focused his research on vulnerability and risk assessment of built environment from natural hazards (earthquakes, floods, tsunami and volcanic ash). He has also been a part of several international initiatives, such as the Global Earthquake Model, the Greater Metro Manila Risk Assessment, the UNISDR Global Assessment Report and the Earthquake Risk Assessment in Pakistan. He has conducted numerous post-disaster surveys after damaging events (earthquakes, floods, cyclones, storm surges) in several countries. He has published several papers in international refereed conferences and reputed journals.

Mr Martin Wehner

Mr Wehner is a structural engineer at Geoscience Australia. He has 22 years of experience as a practising structural engineer designing buildings of all sizes and types both in Australia and internationally. Since joining Geoscience Australia in 2009 his research work has centred on the vulnerability of structures to flood, wind and earthquake. He has participated in post-disaster damage surveys to Padang (Earthquake), Brisbane (Flood), Kalgoorlie (Earthquake) and Christchurch (Earthquake). In each case he has led the post-survey data analysis to develop vulnerability relationships and calibrate existing relationships. He has led the development of Geoscience Australia’s suite of flood and storm surge vulnerability curves. He is a Member of Engineers Australia and IABSE.

END-USERS

End-user organisation	End-user representative	Extent of engagement (Describe type of engagement)
Geoscience Australia	Leesa Carson	
Fire and Rescue NSW	Greg Buckley	
Department of Fire and Emergency Services, WA	Jackson Parker	
Office of Environment and Heritage, NSW	Duncan McLuckie	
Metropolitan Fire Service, SA	Greg Howard	
NSW Rural Fire Service	Corey Shackleton	
NSW State Emergency Service	Elliott Simmons	

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APPENDIX A: STOREY TYPE 1 - TIMBER FRAME (RAISED FLOOR)

<u>Typical building drawings</u>

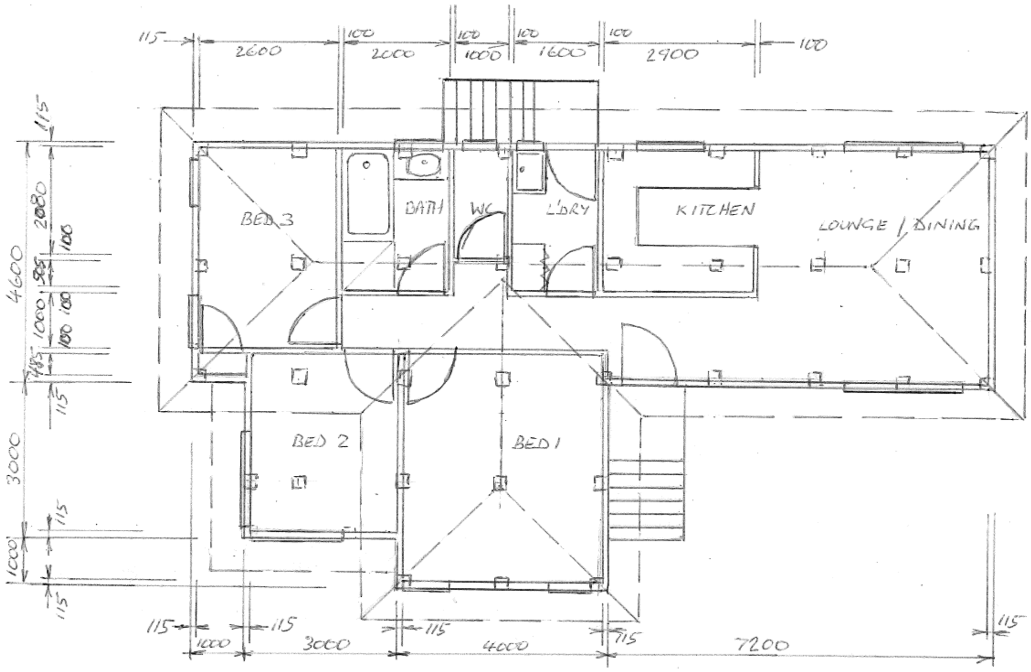

Figure A1: Floor plan

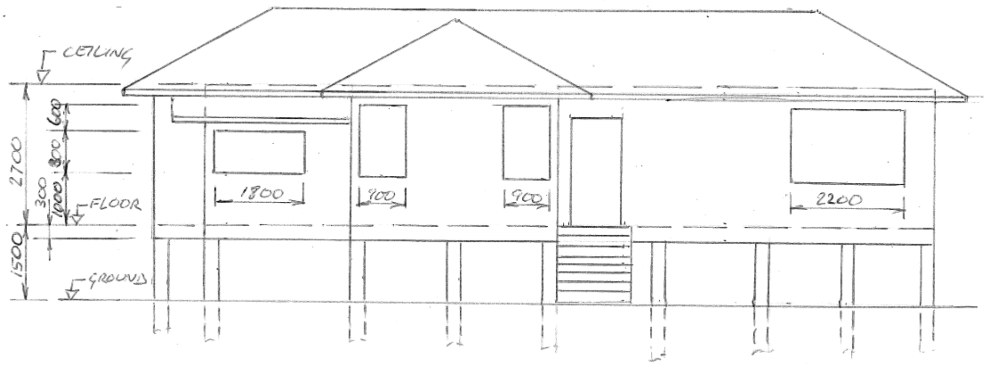

Figure A2: Front elevation

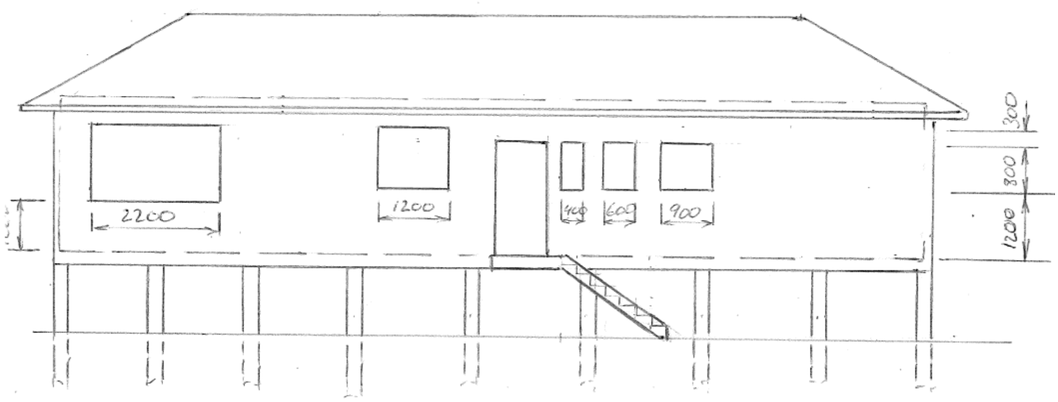

Figure A3: Back elevation

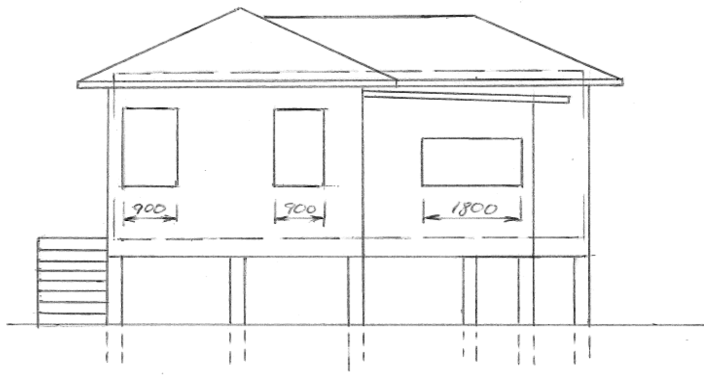

Figure A4: West elevation

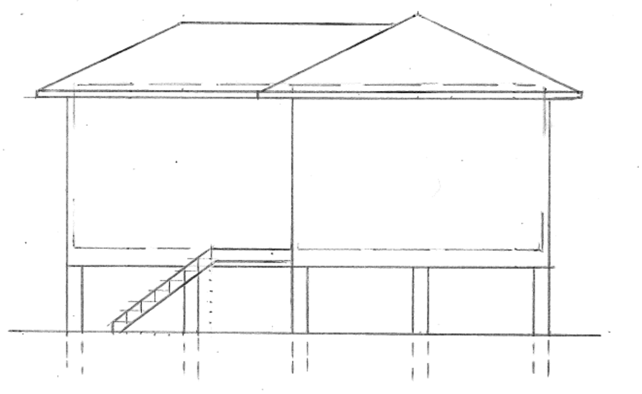

Figure A5: East elevation

APPENDIX B: STOREY TYPE 2 - VICTORIAN TERRACE (RAISED FLOOR)

<u>Typical building drawings</u>

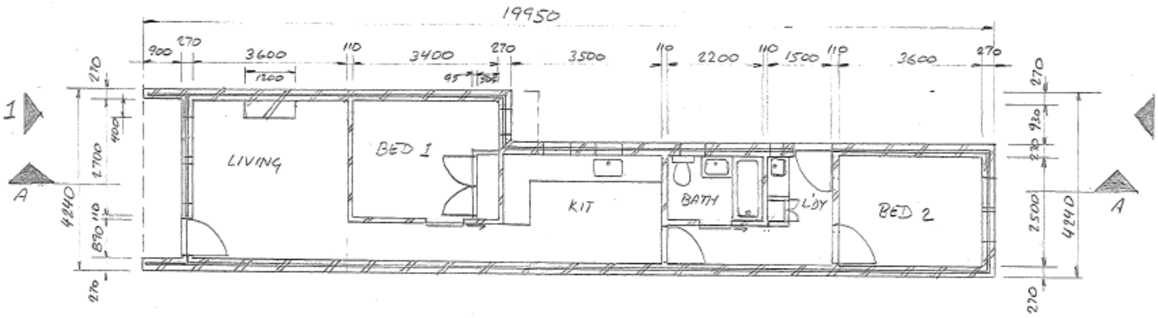

Figure B1: Floor plan

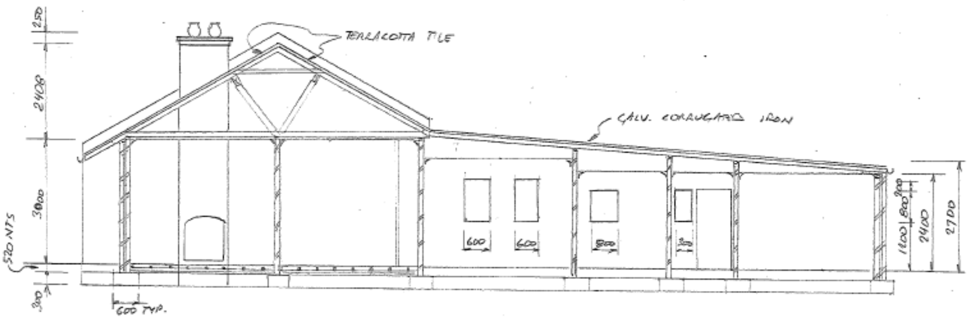

Figure B2: Section A-A

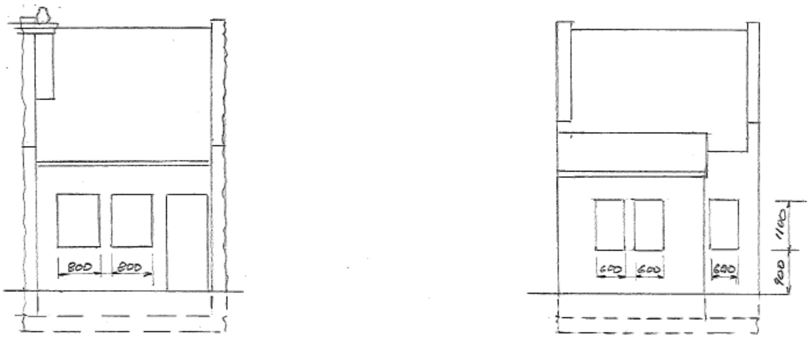

Figure B3: Front (1) and back (2) elevations

APPENDIX C: STOREY TYPE 3 - CAVITY MASONRY (RAISED FLOOR)

Typical building drawings

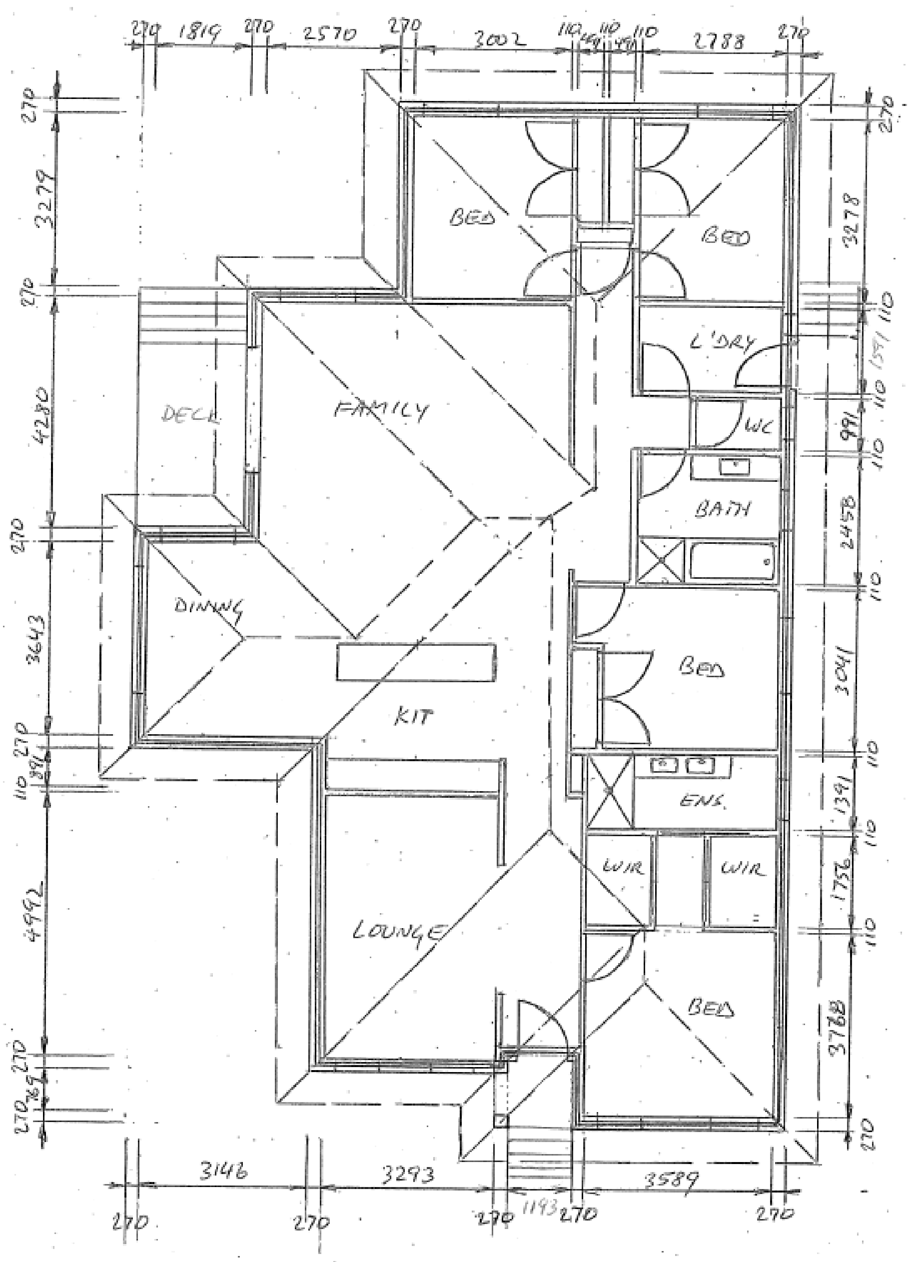

Figure C1: Floor plan

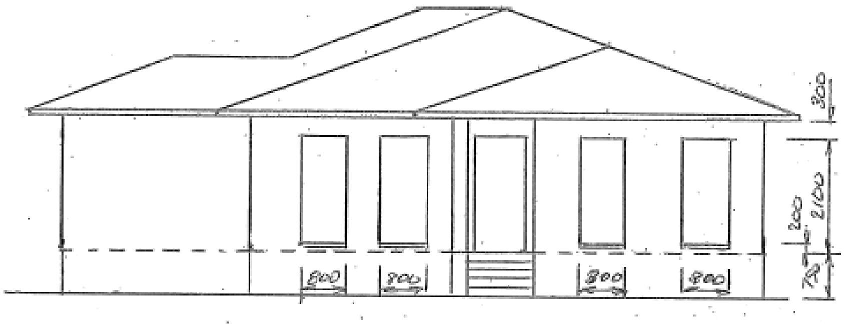

Figure C2: Front elevation

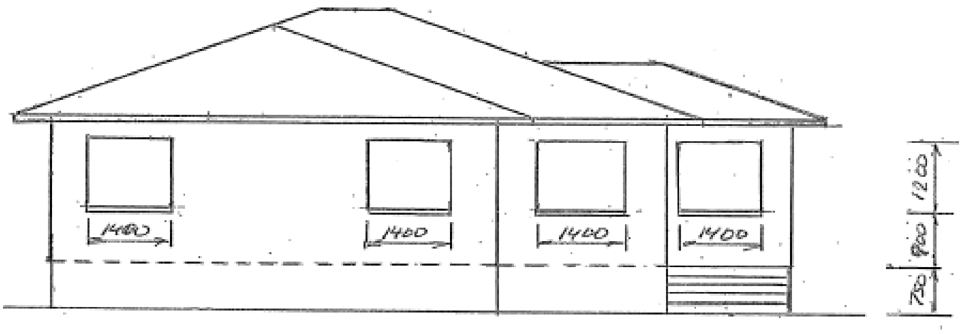

Figure C3: Back elevation

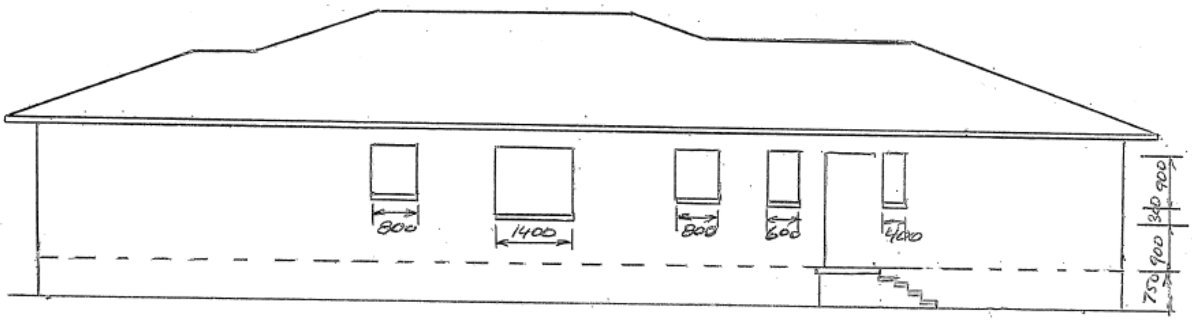

Figure C4: East elevation

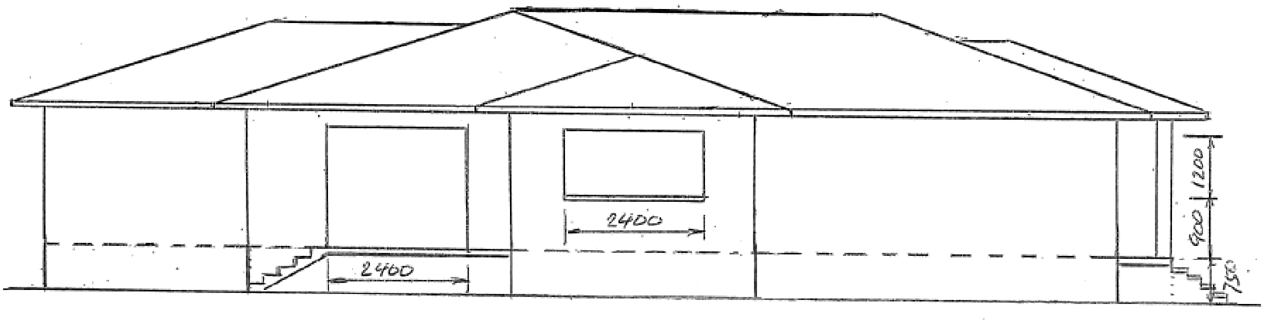

Figure C5: West elevation

APPENDIX D: STOREY TYPE 4 - BRICK VENEER (RAISED FLOOR)

Typical building drawings

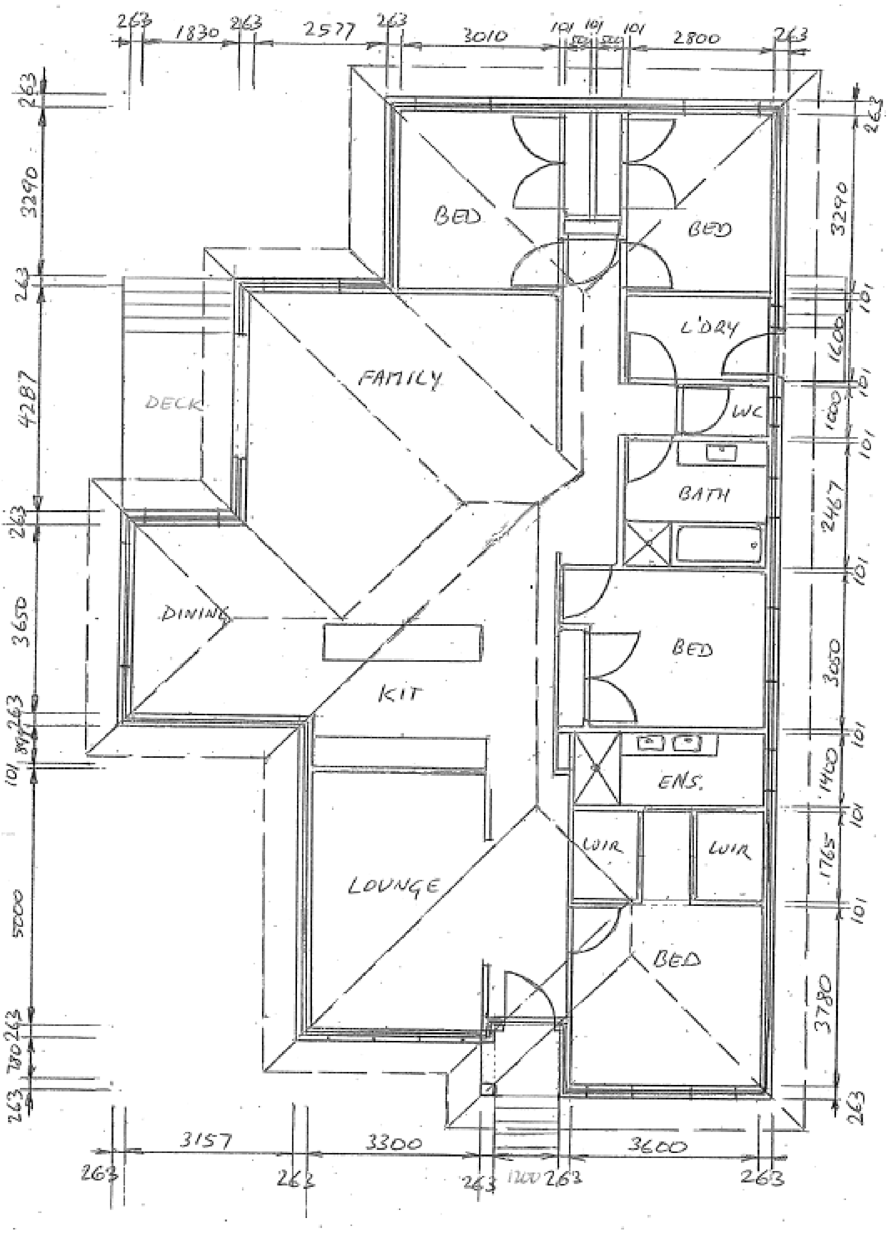

Figure D1: Floor plan

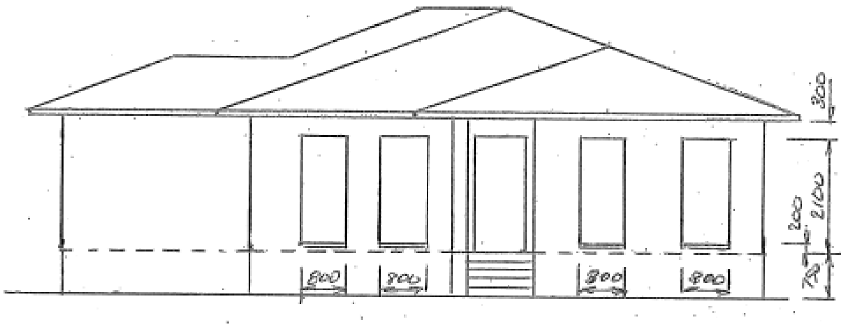

Figure D2: Front elevation

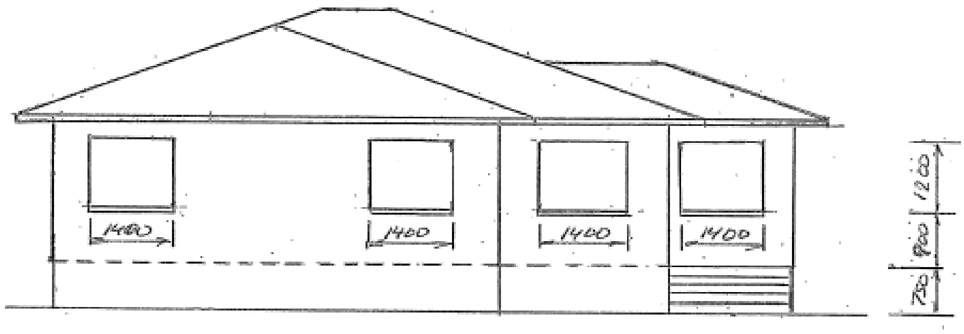

Figure D3: Back elevation

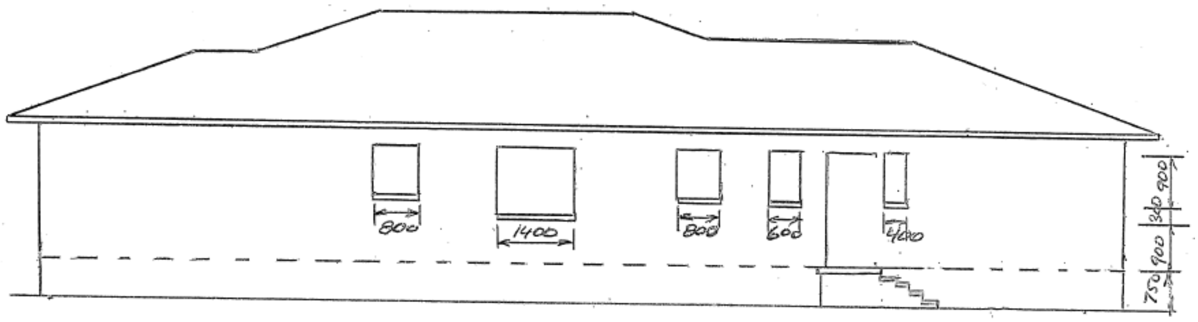

Figure D4: East elevation

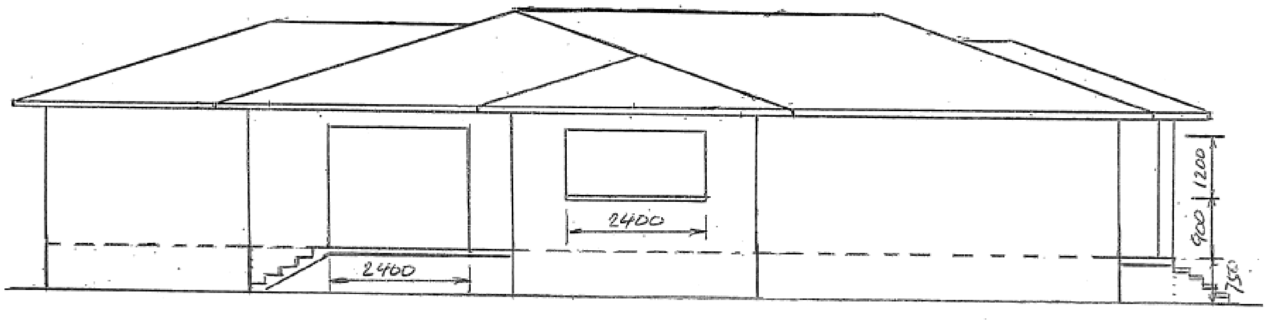

Figure D5: West elevation

APPENDIX E: STOREY TYPE 5 - BRICK VENEER (SLAB-ON-GRADE)

Typical building drawings

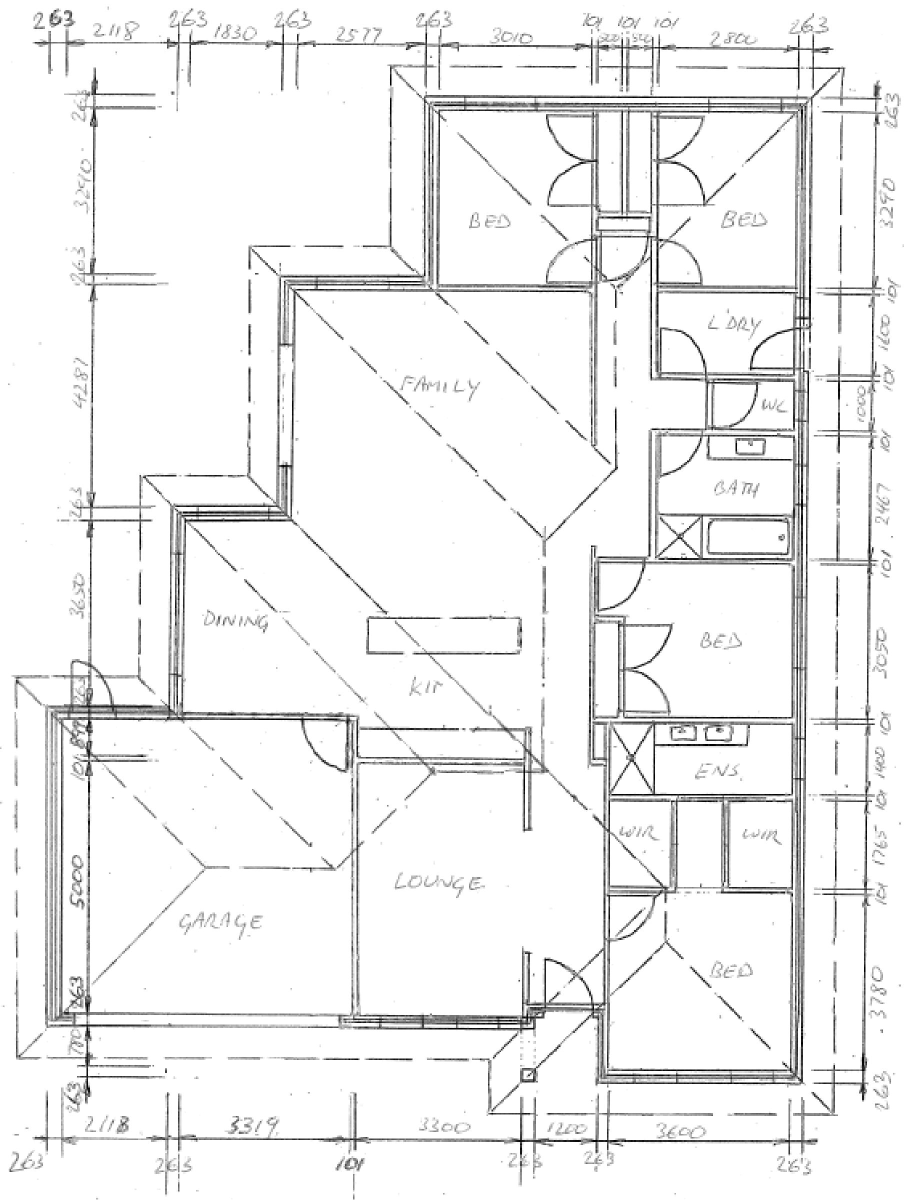

Figure E1: Floor plan

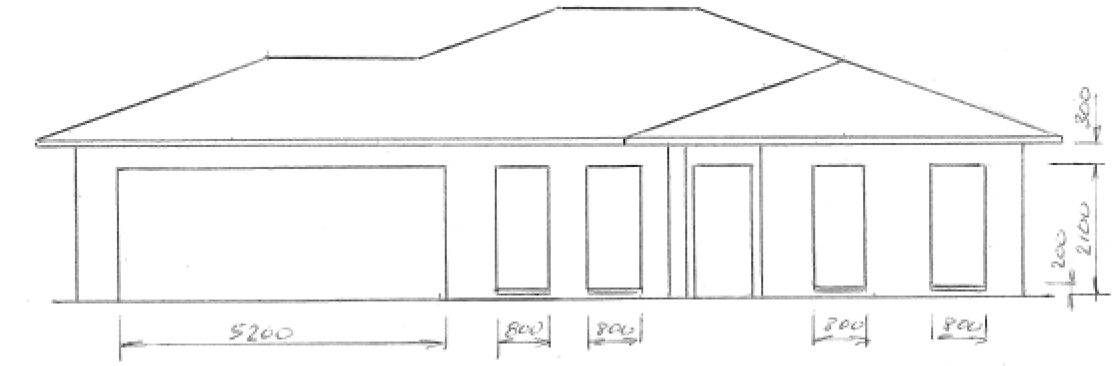

Figure E2: Front elevation

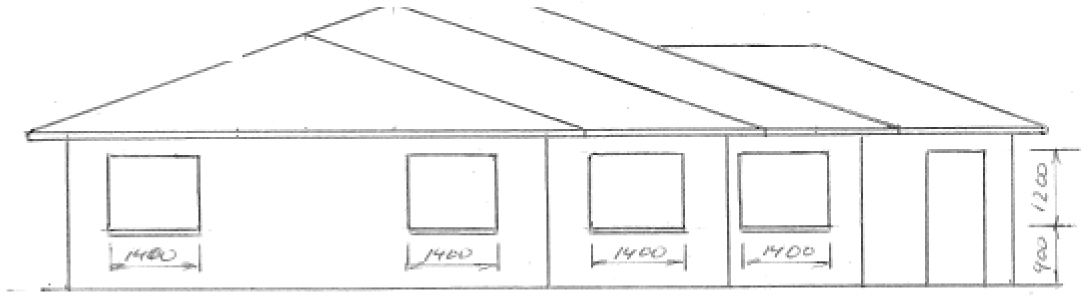

Figure E3: Back elevation

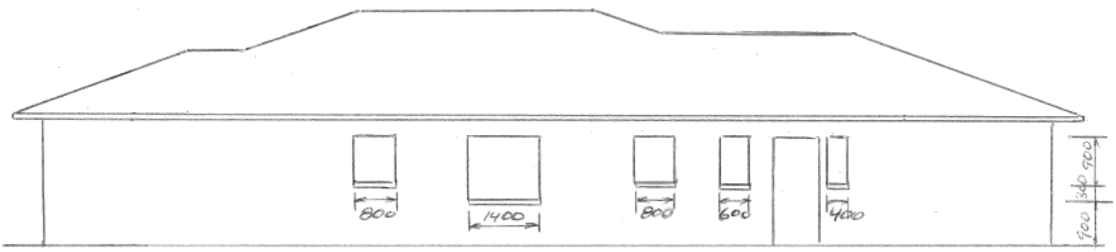

Figure E4: East elevation

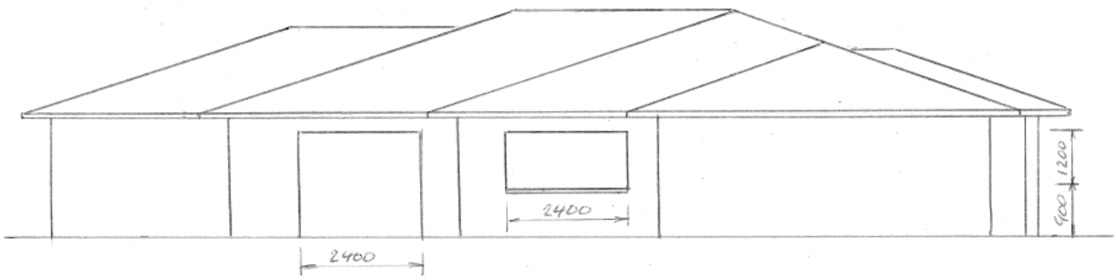

Figure E5: West elevation

APPENDIX F: BENEFIT COST RATIO TABLES

TABLE F1: BENEFIT VERSUS COST TABLES FOR STOREY TYPE 1

Mitigation Option	3% Discount Rate			5% Discount Rate			7% Discount Rate		
	Launceston	Brisbane	Hunter	Launceston	Brisbane	Hunter	Launceston	Brisbane	Hunter
WFP-EXS	-0.56	0.97	1.13	-0.37	0.63	0.73	-0.27	0.46	0.53
WFP-RNV	0.61	0.86	0.93	0.40	0.56	0.61	0.29	0.41	0.44
ELE	5.69	3.27	3.03	3.69	2.12	0.61	2.68	1.54	0.44

TABLE F2: BENEFIT VERSUS COST TABLES FOR STOREY TYPE 2

Mitigation Option	3% Discount Rate			5% Discount Rate			7% Discount Rate		
	Launceston	Brisbane	Hunter	Launceston	Brisbane	Hunter	Launceston	Brisbane	Hunter
WFP-EXS	0.01	0.05	0.05	0.01	0.03	0.03	0.01	0.02	0.02
WFP-RNV	0.10	0.10	0.10	0.07	0.07	0.06	0.05	0.05	0.05
ELE (NEW STOREY)	1.21	0.72	0.66	0.79	0.46	0.43	0.57	0.34	0.31
TEMP900	0.21	0.29	0.39	0.14	0.19	0.25	0.10	0.13	0.18
TEMP1200	0.59	0.30	0.33	0.38	0.20	0.22	0.27	0.14	0.15
PERM1000	0.31	0.30	0.34	0.20	0.19	0.22	0.15	0.14	0.16

TABLE F3: BENEFIT VERSUS COST TABLES FOR STOREY TYPE 3

Mitigation Option	3% Discount Rate			5% Discount Rate			7% Discount Rate		
	Launceston	Brisbane	Hunter	Launceston	Brisbane	Hunter	Launceston	Brisbane	Hunter
WFP-EXS	-0.52	0.79	0.99	-0.34	0.52	0.64	-0.24	0.37	0.47
WFP-RNV	0.20	0.44	0.51	0.13	0.29	0.33	0.09	0.21	0.24
ELE (NEW STOREY)	1.26	0.72	0.66	0.82	0.46	0.43	0.59	0.34	0.31

TABLE F4: BENEFIT VERSUS COST TABLES FOR STOREY TYPE 4

Mitigation Option	3% Discount Rate			5% Discount Rate			7% Discount Rate		
	Launceston	Brisbane	Hunter	Launceston	Brisbane	Hunter	Launceston	Brisbane	Hunter
WFP-EXS	-0.24	-0.26	-0.24	-0.16	-0.17	-0.16	-0.11	-0.12	-0.11
WFP-RNV	0.61	0.39	0.36	0.39	0.25	0.23	0.29	0.18	0.17
ELE (NEW STOREY)	1.19	0.62	0.58	0.77	0.40	0.37	0.56	0.29	0.27

TABLE F5: BENEFIT VERSUS COST TABLES FOR STOREY TYPE 5

Mitigation Option	3% Discount Rate			5% Discount Rate			7% Discount Rate		
	Launceston	Brisbane	Hunter	Launceston	Brisbane	Hunter	Launceston	Brisbane	Hunter
WFP-EXS	2.02	1.43	1.32	1.31	0.93	0.86	0.95	0.67	0.62
WFP-RNV	0.21	0.15	0.14	0.14	0.10	0.09	0.10	0.07	0.07
ELE (NEW STOREY)	1.22	0.64	0.57	0.79	0.41	0.37	0.57	0.30	0.27
TEMP900	0.67	0.83	1.24	0.43	0.54	0.80	0.30	0.37	0.55
TEMP1200	2.54	1.10	1.26	1.65	0.71	0.81	1.14	0.49	0.57
PERM1000	1.46	1.25	1.45	0.95	0.81	0.94	0.69	0.59	0.68