Resilient Buildings: Informing Maintenance for Long-term Sustainability

Final Research Report

Part 3: Maintenance and resilience of buildings for flood risks

Prepared by Palaneeswaran Ekambaram and Lam Pham; *Swinburne University of Technology*

Research Project: P1.53 Resilient buildings: Informing maintenance for long-term sustainability

Project Leader: Lam Pham

Research Team:
Lam Pham and Palaneeswaran Ekambaram; *Swinburne University of Technology, Victoria*
Rodney A. Stewart, Oz Sahin, Edoardo Bertone, Juliana Faria Correa Thompson Flores; *Griffith University, Queensland*

Date: September 2018

OUTLINE OF THE FINAL RESEARCH REPORT

The Final Research Report of SBEnrc Project 1.53 Resilient buildings: Informing maintenance for long-term sustainability is presented in the following set of separate documents:

Part 1: Overview of extreme events and maintenance

Part 2: Maintenance and resilience of buildings for bushfire risks

Part 3: Maintenance and resilience of buildings for flood vulnerabilities

Part 4: Development of a maintenance prevention strategy to mitigate wind-driven rainwater ingress through windows and external glazed doors in social housing

This Part 3 of the Final Report includes:

(a) An overview on flood types and actions impacting buildings;
(b) A summary on building damage due to flood vulnerabilities;
(c) A synopsis on planning and governance for preventive mitigation;
(d) A section on design for maintaining against flood risks;
(e) A discussion on maintenance for flood resilience of buildings; and
(f) A set of recommendations on building resilience for flood risks and suggestions for their implementation.

Further Information and other reports: http://sbenrc.com.au/research-programs/1-53/

Acknowledgements

Project Steering Group members, SBEnrc and industry representatives

Graeme Newton	PSG Chair
Carl Barrett	BGC Australia
Dan Gardiner	BGC Australia
Sarah Mewett	Department of Communities, WA
Veronica Pannell	Department of Communities, WA
Carolyn Marshall	Department of Finance, WA
Dean Wood	Department of Finance, WA
Rosemary Axon	Dept. of Housing & Public Works, QLD
Dean Luton	Dept. of Housing & Public Works, QLD
Jessica Dominguez	Land and Housing Corporation, NSW
Martin Nunez	Land and Housing Corporation, NSW
Emad Gad	Swinburne University of Technology
Keith Hampson	SBEnrc
Debbie Thackray	SBEnrc
Lauren Gubbin	SBEnrc

Project Affilate - Australasian Fire and Emergency Services Authorities Council (AFAC) and participants/ persons consulted from various stakeholder organisations including Australian Windows Association, Australian Building Codes Board (ABCB), Commonwealth Scientific and Industrial Research Organisation (CSIRO), Department of Fire and Emergency Services (DFES) – Western Australia, and Facilities Management Association of Australia (FMA).

EXECUTIVE SUMMARY

SBEnrc project P1.53 Resilient Buildings: Informing Maintenance for Long-term Sustainability aimed to examine the role of maintenance in making buildings more resilient to extreme weather events, cyclones/storms, bushfires and floods, using technical knowledge to inform policy and practice. The focus was on existing low-rise public buildings. Part 3 examines building resilience for flood extremes, and considers building losses, regulation, risk assessment and the role of maintenance in reducing risk.

Key recommendations are:

1. All properties (including buildings and landscaping) in flood prone areas should be maintained through continuous monitoring and routine maintenance of critical components.
2. Maintenance checklists of critical components for the properties should be developed. These need to be integrated with appropriate databases and systems for routine/continuous condition monitoring and maintenance decisions for flood resilience. The checklist should cover building structural elements (e.g. foundations, floors, walls and roofs), utilities and non-structural fixtures (e.g. drains, gutters, plumbing and electrics) and landscape architecture within the property.
3. Strict regulatory controls for building permits and 'mature' governance of maintenance for flood resilience need to be developed.
4. All new designs should include responsible design for maintainability, embracing flood resistance and/or flood resilience aspects. In addition, responsive construction and maintenance should be considered, embracing relevant flood resilient technologies and materials in new constructions and retrofitting of existing ones for resilience.
5. Flood resilient planning agendas should be developed for new developments and maintaining existing building assets.
6. A 'smart' systems approach with development of maintenance manuals, smart systems and integrated databases linked with building information and lifecycle cost-based predictive/ decision-support models is required for futureproof resilience for flood vulnerabilities.
7. As a non-mandatory arrangement for foolproof flood resilience, certifications for the maintenance supply chain and flood resilience products/materials could be considered.

Table of Contents

1 Introduction 5

2 Flood types and actions 6

2.1 Flood types 6

2.2 Flood forces and actions 7

2.3 Flood-related emerging Risks 8

2.3.1 Mudslides and mudflows 8

2.3.2 Flood after bushfires 8

3 Flood damage to buildings 10

3.1 Overview of flood vulnerabilities impacting buildings 10

3.2 Typical building damage from flood impacts 10

4 Planning and governance for preventive mitigation 11

5 Design for maintenance against flood vulnerabilities 15

5.1 Design buildings for avoidance of flood impacts 15

5.2 Design buildings for flood resistance 15

5.3 Design buildings for flood resilience 16

5.4 Design for maintainability and resilience of buildings against flood risks 16

5.5 Some examples from international codes, ASCE and FEMA, USA 18

6 Maintenance for flood resilience 20

6.1 Complexities and challenges in maintenance 20

6.2 Safety evaluation and checklists to repair flood damage in buildings 21

6.3 Routine inspection and maintenance for flood resilience of buildings 22

6.4 Predictive maintenance and smart integration with intelligent systems 22

6.5 Retrofitting to enhance flood resilience of buildings 22

6.6 Build back better approach for maintenance and sustainable resilience 23

7 Recommendations 24

7.1 Suggestions for implementation of the recommendations 24

8 References 26

1 INTRODUCTION

Natural flood and water ingress vulnerabilities from high winds such as severe storms and cyclones cause significant damage to low-rise building stock in Australia (Pham et al. 2018). The Bushfire and Natural Hazard Cooperative Research Centre (BNHCRC) has reported that floods are the most financially costly and the second deadliest natural hazard in Australia (BNHCRC, 2017). Reports such as BTE (2001) and Handmer et al. (2016) revealed that floods are common and recurrent extreme events in all States and Territories in Australia.

Most buildings and building components are not designed for flooding and water/moisture ingress issues. Flood entry routes into buildings can be through: (a) masonry and mortar joints where natural permeability is high; (b) vents, air bricks/hollow blocks and flaws in wall constructions; (c) openings such as windows and doors as well as vulnerable gaps/cracks in the connections of walls and frames; (d) door thresholds, for example those lowered to the ground to allow easy/level access; (e) gaps around wall outlets and voids for utility services such as water/gas pipelines, heating and ventilation systems, electricity/telephone cables; (f) flaws in damp-proof courses; (g) underground seepage; or (h) backflow from drainage systems/sanitary appliances (Garvin, 2012a). The tangible impacts of floods on buildings are acute (immediate and short-term) and/or chronic (long-term damage and deterioration), whilst intangible impacts such as the stress of dealing with builders/repairers/insurers, emotional losses and fear regarding resilience for future floods are not easily quantifiable (Garvin and Hunter, 2014). Furthermore, increased demand for new housing and non-residential buildings may increase pressures to build in areas at risk to floods that correlate to areas of higher deprivation (Environment Agency, 2018). Climate change effects may further increase flood occurrences and associated risks. Relevant strategies and adequate measures to ensure and enhance resilience of buildings are required, especially for those properties in areas of high flood risks (Bonfield, 2016).

Safety is of paramount priority for buildings in locations prone to natural disasters such as floods (FEMA 2007, International Codes Council, 2014). Flood performance of buildings can be improved through resilience focused planning, designing, constructing and maintenance arrangements/activities (e.g. DCLG, 2007, FEMA 2010a, FEMA 2011a, FEMA2011c).

2 FLOOD TYPES AND ACTIONS

2.1 Flood types

Australia is the sixth largest country in the world with: (i) more than 7.6 million square kilometres in area; (ii) around 34250 kilometres of coastline; and (iii) a range of climate zones including equatorial, tropical, subtropical, desert, grassland and temperate (e.g. the seven climate zones classified by the Australian Standard Geographical Classification[1] and the eight climate zones classified by the Australian Building Codes Board[2]). The complexities and uncertainties of flood risks are diverse across Australia, due to variable rainfall, climate change effects, cyclones and so on.

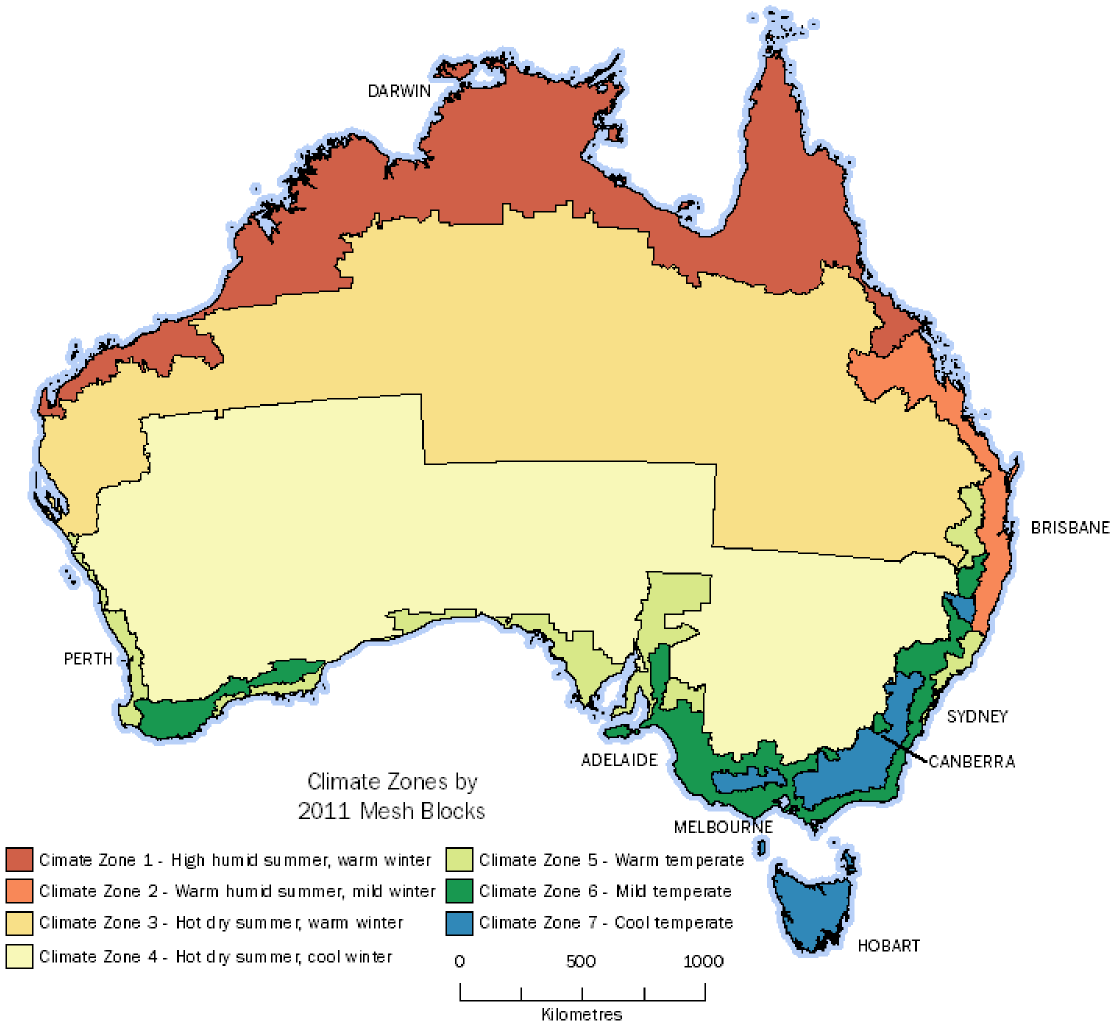


Figure 1. Australian regions and climate zones (Figure source: Australian Bureau of Statistics)

[1] http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/by%20Subject/4671.0~2012~Main%20Features~Climate%20zone~17

[2] https://www.abcb.gov.au/Resources/Tools-Calculators/Climate-Zone-Map-Australia-Wide; and http://www.yourhome.gov.au/introduction/australian-climate-zones

The following flood types described in the literature, such as in ATC (2004) and Garvin and Hunter (2014), are applicable in Australia:

- Fluvial (River) flooding – when a watercourse swells due to heavy and/ or prolonged rainfall causing overflows.
- Pluvial flooding – when substantial water pools on the ground surface (e.g. when rainwater is unable to drain through normal drainage systems or soak into the ground; *Note: this is often not covered in flood risk maps).*
- Closed-basin flooding – when a closed body of water (e.g. a lake or a pond) receives excessive runoff (sudden/continuous) from associated catchment and drainage systems.
- Flash flooding – when a rapid overland flow of water occurs in a short period of time (e.g. within a few minutes after a rainstorm onset), which may be due to localised excessive/high intensity rainfall in catchment areas.
- Sewer (drainage) flooding – when drainage pipes and sewer capacities are not adequate to cope with excessive rainfall, which is a frequent issue in dense urban regions or through unresolved maintenance issues (e.g. blocked stormwater drains).
- Coastal flooding – when inundation of land occurs in coastal regions (e.g. due to storms and cyclones or high astronomical tides coinciding with a storm tidal surge driven by wind and atmospheric pressure).
- Groundwater flooding – when ground water levels rise above the surface (e.g. in regions with aquifers and permeable rock strata).

2.2 Flood forces and actions

Floods can damage structures and non-structural components of buildings due to a range and combination of flood forces/actions and the following are compiled from the literature (e.g. ATC, 2004; New South Wales Government, 2007; and Garvin and Hunter, 2014):

- Hydrostatic forces and resultant actions
    - Lateral pressure; e.g. when water covers part of or an entire building's components (such as a wall) on one side, resulting in linear pressure over the entire component or asymmetrically
    - Capillary rise; e.g. when water adheres to the surface/cavities of walls and capillary action causes some local and upward movement of dampness/wetness
- Hydrodynamic forces and resultant actions
    - Lateral pressure caused by water flowing around a building

    - Suction by localised water velocity or changes in velocity/pressure; e.g. around corners and through gaps
    - Turbulence due to irregular fluctuations in velocity
    - Waves
        - Non-breaking waves (increase and decrease of pressure/force exerted by the peaks and troughs)
        - Breaking wave (waves breaking in, over, through or near a building by which large pressures are imparted dynamically)
- Buoyancy and resultant actions; the buoyancy force is a vertical uplifting force that can make the whole building (e.g. lightweight sheds) or its components (e.g. pipes, storage tanks) float or cause other damage such as cracking, destabilisation and complete collapse
- Impact forces of floating debris and resultant actions
    - Static actions; e.g. sediment accumulation inside or outside the building
    - Dynamic actions; including concentrated and distributed forces
    - Erosion actions; e.g. associated with dragged soils/gravels/other debris
- Non-physical actions; such as chemical (e.g. rust and corrosion of reinforcement) and biological elements (e.g. mould from singular/multicellular fungi and timber decay)

2.3 Flood-related emerging Risks

2.3.1 Mudslides and mudflows

Mudslides can occur when flood runoff on a steep slope entrains large quantities of loose sediments and debris (e.g. uprooted trees and branches or boulders) and flows rapidly down slopes (ATC 2004).

Mudflows can occur when rivers of liquid and flowing mud are caused by a combination of brush loss and subsequent heavy rains. Rapid snow melt can also trigger mudflows (FEMA, 2017a). Mudflows often come in the wake of wildfires that destroy vegetation needed to support and strengthen hillsides. They can occur quickly and with little warning, destroying lives and property (FEMA, 2018b).

2.3.2 Flood after bushfires

Bushfires/forest fires/wildfires can drastically alter the terrains and significantly increase the risk for floods over a period of time. The following extracts from FEMA (2017a) and FEMA (2017b) are potentially relavant to certain critical regions in Australia:

- Large-scale wildfires dramatically alter the terrain and ground conditions.
- Flooding after a wildfire is a one-two punch. … The ground can no longer absorb water, so even light rain can lead to devastating flash flooding and mudflows.

- Normally, vegetation absorbs rainfall, reducing runoff. However, wildfires leave the ground charred, barren and unable to absorb water, creating conditions ripe for flash flooding and mudflow.
- Flood risk remains significantly higher until vegetation is restored – up to 5 years after a wildfire.
- Flooding after fire is often more severe, as debris and ash left from the fire can form mudflows.
- As rainwater moves across charred and denuded ground, it can also pick up soil and sediment and carry it in a stream of floodwaters. This can cause more significant damage.

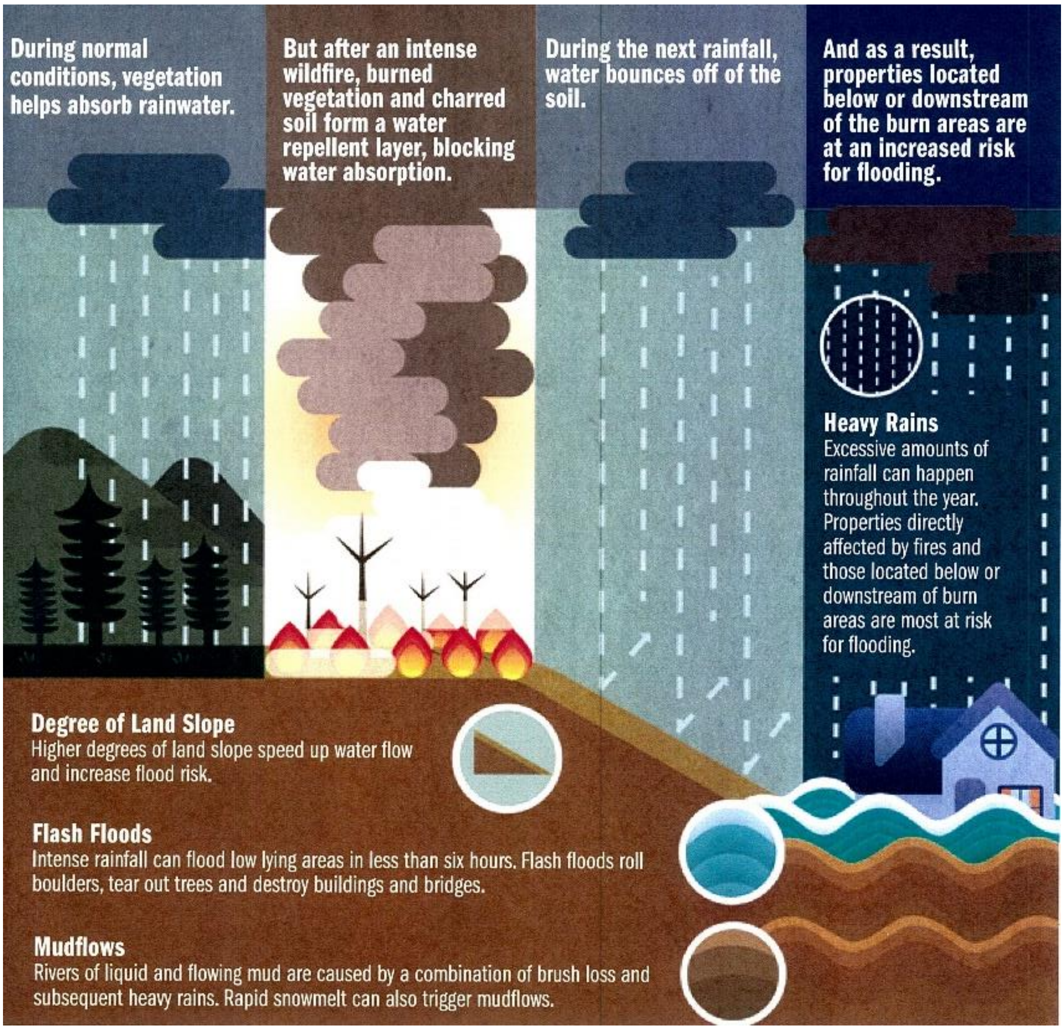


Figure 2. An emerging risk of flood after bushfires (Figure Source: FEMA, 2017b)

3 FLOOD DAMAGE TO BUILDINGS

3.1 Overview of flood vulnerabilities impacting buildings

Flood damage to structures and non-structural components is mainly due to: hydrostatic and hydrodynamic forces, erosion and scour, debris impact, water ingress and moisture absorbance issues. In addition, waves are a concern for buildings in coastal regions and in other flooded regions, especially due to high winds or movement of floating objects including debris and boats. However, wave action is not considered in most of the hydraulic models and flood risk assessments. Damage due to trapped mud and moisture as well as mould issues is also significant. Furthermore, the extent and duration of flood exposure can increase the risk of damage. Multi-hazard occurrences can enhance the risk levels; for example, flood after cyclone/ windstorm, flood after flood, flood after fire, flood after mudflow and flood after a serious hailstorm.

3.2 Typical building damage from flood impacts

Typical types of building damage from flood impacts include:

- Damage to foundations from flood-related geotechnical/soil failures; e.g. soil erosion, soil piping, and swelling of soil after inundation followed by subsequent shrinking after drainage.
- Damage to walls and building components; e.g. cracks in plaster board, damp wall cavities, jamming/warping of doors and windows, flaking/blistering of painting and finishes, movement of frames/stumps, lifting of tiles, lifting of flooring and decay of joists.
- Damage to floors; e.g. lifting of flooring, decay of joists, springy floor boards, sub-floor moisture ingress.
- Damage to utilities and non-structural components; e.g. damage to HVAC (heating, ventilation and air conditioning), plumbing, electrical and mechanical systems.

Information in the literature, such as ATC (2004) and New South Wales Government (2007), provides further details of building damages due to different flood forces and actions.

4 PLANNING AND GOVERNANCE FOR PREVENTIVE MITIGATION

Floods are common and recurrent extreme events in all States and Territories in Australia. Common categories experienced are riverine floods and coastal floods. In general, most parts of buildings are not planned and designed to withstand flooding.

Currently, regulations allow buildings to be erected in flood prone areas for Class 1 (i.e. houses such as standalone terrace houses, row houses, and townhouses), 2 (i.e. apartments/multi-unit residential buildings), 3 (includes residential buildings other than Class 1 or Class 2; e.g. boarding house, guest house, hostel), 9a (hospitals/healthcare buildings) and 9c (aged care buildings) (ABCB, 2017). Although capital costs (such as cheaper land costs) might be seen as a compelling attraction for development, avoiding flood-prone areas for new buildings is recommended, especially for those with high flood-risk vulnerabilities such as aged care facilities and hospitals.

Useful parameters and benchmarks for planning buildings resilient for flood hazards (e.g. Melbourne Water, 2007; New South Wales Government, 2007; ABCB, 2012; ABCB, 2016; AIDR, 2017) include:

- Annual Exceedance Probability (AEP), which is the likelihood of the occurrence of a flood of a given (or larger) extent occurring in any one year.
- Australian Height Datum (AHD), which refers to a common national survey height datum as a reference level for defining reduced levels (e.g. 0.0 meters of AHD for the sea level).
- Probable Maximum Flood (PMF), which is the largest flood that could conceivably be expected to occur at a particular location, usually estimated from probable maximum precipitation. The PMF defines the maximum extent of flood prone land/ floodplain and the AEP for the PMF is commonly assumed to be of the order of 104 to 107 i.e. once in 10,000 to 10,000,000 years (NSW SES, 2018).
- Defined Flood Event (DFE), which refers to a flood event selected for the management of flood hazard for the location of specific development as determined by the appropriate authority.
- Defined Flood Level (DFL), which is the flood level associated with a DFE, i.e. defined flood event.
- Freeboard, which is the height above the DFL as determined by the appropriate authority; the freeboard is useful to compensate for effects such as wave actions and localised hydraulic behaviour of flood waters.
- Flood Planning Level (FPL) is a combination of DFL and freeboard selected for the floodplain management.

- Probable Maximum Flood (PMF), which is the largest flood that could occur in a particular location that can be estimated from probable maximum precipitation, snow melt and catchment conditions.

For example, the National Construction Codes (ABCB 2016 and ABCB 2018) emphasise that the floor level in non-habitable floor areas should not be more than 1 meters below the DFL and the lowest habitable floor level of a building (all classes) should be above the DFL by the freeboard height determined/prescribed by the appropriate authority.

Comprehensive integrated planning of floodplains and developments/upgrades (both building and infrastructure) is valuable for effective prevention and efficient mitigation of flood impacts. Consultations with communities and stakeholders will be useful for consensus and collaborations.

A range of useful information sources for planning and governance policies is available, such as:

- The Bureau of Meteorology provides various weather information and warnings for flood in Australia.
- Geoscience Australia provides useful arrangements such as the Australian Flood Risk Information Portal and the Australian Flood Studies Database.
- Reports such as CSIRO (2000), Queensland Reconstruction Authority (2012), AIDR (2017) provide useful information and insights for developing/updating planning measures and governance policies to minimise the flood impact mitigation requirements.
- Lessons learned from major incidents, such as from the Australian Institute for Disaster Resilience (e.g. AIDR, 2017), can provide useful insights.

Useful references for planning and estimating the riverine/ coastal flood vulnerabilities include: HAZUS flood technical manual and a range of vulnerability functions available within the HAZUS (FEMA 2011b).

International guidelines, reports and legislation can be useful benchmarking tools. Examples include the European Union Floods Directive, UK Environment Agency report on National Flood and Coastal Erosion Risk Management Strategy, UK House of Commons reports on Future Flood Prevention (HC 2017a) and Flood and Water Management Act 2010 (HC 2017b), and the USA Federal Emergency Management Agency (FEMA) Policy Standards for Floor Risk Analysis and Mapping.

An example of the regulatory responsibilities and policy governance for managing flood risks in the UK (HM Government, 2016) is below:

- The UK Environment Agency is responsible for strategic overview of the management of all sources of flooding and coastal erosion, which includes setting the direction for managing the risks through strategic planning; working collaboratively to support the development of risk management skills and capacity; and providing a framework to support local delivery.
- Lead Local Flood Authorities are responsible for: developing, maintaining and applying a strategy for local flood risk management in their areas and for maintaining a register of flood risk assets; and lead responsibility for managing the risk of flooding from surface water, groundwater and ordinary watercourses.
- District Councils are key partners in planning local flood risk management and can carry out flood risk management works on minor watercourses.
- Internal Drainage Boards, which are independent public bodies responsible for water level management in low lying areas, also play an important role in the areas they cover (approximately 10% of England at present), working in partnership with other authorities to actively manage and reduce the risk of flooding.
- Highway Authorities are responsible for providing and managing highway drainage and roadside ditches, and must ensure that road projects do not increase flood risk.
- Water and Sewerage Companies are responsible for managing the risks of flooding from water and foul or combined sewer systems providing drainage from buildings and yards.
- Department of Communities and Local Government through Local Planning Authorities have a key role in the planning process to ensure flood risk is appropriately taken into account in the planning process.
- Under the Flood and Water Management Act 2010, all risk management authorities have a duty to co-operate with each other and to share data.

Although the extent and severity of flood risks vary across different Australian States and Territories, developing a set of uniform standard guidelines and governance policies can be useful; for example for council approvals for new buildings in high risk zones, design and construction practice and insurance purposes. The planning measures and governance policies should have integrative consideration for multi-hazard risks such as bushfire, windstorm and flood.

According to the National Institute of Building Sciences (2017), a useful public-sector mitigation strategy is to "acquire or demolish flood-prone buildings, especially single-family homes, manufactured homes, and 2- to 4-family dwellings." Also, for flood resistance and addressing riverine flooding and hurricane surge impacts, it refers to building new homes with requirements higher than those required by the 2015 International Building Code. Table 1 presents a set of mitigation priorities for buildings against flood perils.

Table 1. Priorities of mitigation for flood perils (Ref: National Institute of Building Sciences, 2017)

Mitigation Measure	Priority
Elevation	1
Buyout	1
Wet flood proofing	2
Dry flood proofing	3
Land use planning	3
Site perimeter flood proofing	3

The National Infrastructure Commission (2018) has proposed a national standard in the UK so that by 2050, communities will be resilient to flooding 99.5 percent of the time wherever feasible. A similar initiative and holistic support for the drive are required in Australia. Already, the Council of Australian Governments align the policies and strategies in line with COAG (2011). For example, the Queensland Government is committed for development and implementation of a strategic framework for flood risk management (Queensland Government, 2017).

5 DESIGN FOR MAINTENANCE AGAINST FLOOD VULNERABILITIES

Design is significant in a building's resistance capacity and resilience against flood impacts. This section provides an overview of design for maintenance against flood vulnerabilities, specifically with respect to avoidance, resistance, resilience and maintainability aspects.

A two-stage approach could include: (a) determination of floor risk factors such as potential sources of flooding, predicted floor level(s), duration of flood occurrences, frequency of floods, and flooding depth(s); and (b) setting a practical floor level for the building by taking in to account the flood effects on the building/built-environment. For example, Garvin (2012b) suggested considering three flood depth ranges for building design decisions:

i. 0 to 300 mm – design for avoidance and/or resistance for flood impacts
ii. 300 to 600 mm – design for flood resistance in general; if there is a risk of structural collapse, then use a relevant combination with design for resilience; e.g. allow water to enter and pass through
iii. More than 600 mm – design for resilience and use resilient materials for construction and maintenance; lower parts of the building might be resistant

5.1 Design buildings for avoidance of flood impacts

Useful design strategies for avoiding flood impacts on buildings include:

- Siting, site layout and elevating land
- Preventive landscaping and surrounding improvements
- Drainage and soak-away systems
- Impermeable boundary walls
- Raising the lowest floor level of a building with a threshold height above the likely design flood level (e.g. 100 year flood level)

5.2 Design buildings for flood resistance

Flood resistance design considers water exclusion or dry proofing of buildings in which the external walls and openings (such as doors), lowest floor and foundation are designed to prevent water ingress for a targeted design duration.

The factors and parameters for flood-resistant design include depth, velocity and duration of flood, effects of waves and debris, risks for scour/erosion of foundation and other building elements, as well as associated landscape components and all building elements below the design flood elevation.

Aperture and perimeter technologies are considered in flood resistance design and flood resistance arrangements generally embrace:

- Barriers for apertures and perimeters
- Low permeability and water-resistant materials

5.3 Design buildings for flood resilience

Flood resilient design considers wet-proofing for the ability of a building to cope with the hazards of flood-associated risks. For example:

- The use of durable materials that would not be affected by water or water-logged conditions for a design period; also suitable for easy drying and draining.
- Avoiding or minimising cavities and voids in building components such as walls having potential exposure to flood hazards.
- Solid floors and flood-resilient floorings at the lowest/ground floors.

5.4 Design for maintainability and resilience of buildings against flood risks

Designing for maintainability will enhance the resistance and resilience of buildings against flood risks. The following information gained from the recent literature provides examples:

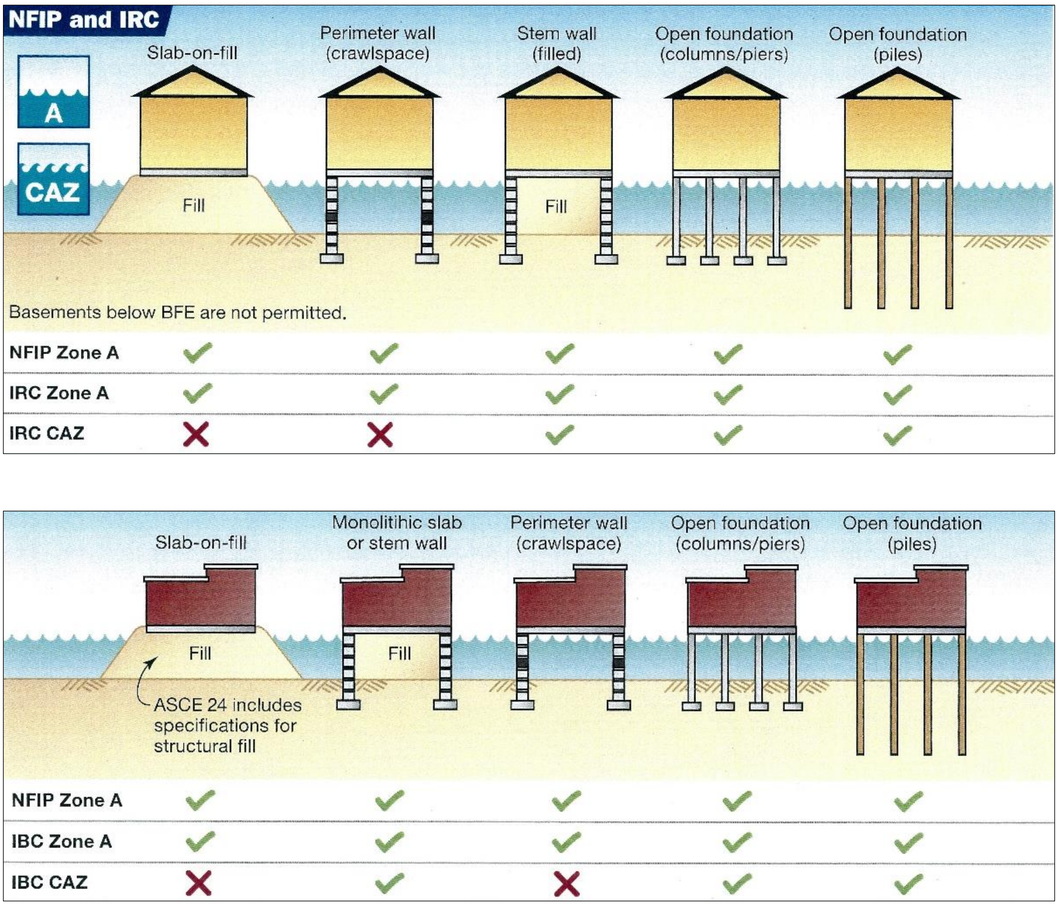
- Building design in flood hazard areas should conform to requirements of standards and guidelines such as Australian Building Codes Board (ABCB, 2012; ABCB, 2016; ABCB, 2018), and standards of American Society for Civil Engineers (ASCE) e.g. ASCE/SCI 24-14 (ASCE, 2014) and ASCE/SCI 7-16 (ASCE, 2017) and guidelines of Federal Emergency Management Agency (FEMA) in USA.
- It will be valuable to consider performance-based flood design in accordance with standards and guidelines such as ASCE/ SEI 24-05 (ASCE, 2006), FEMA 543 (FEMA, 2007), FEMA P798 (FEMA2010a) and FEMA P 424 (FEMA, 2010b).
- Roof drainage design should consider (i) the effects of duration, intensity and frequency of rainfall; (ii) design rain loads and secondary roof drain data; e.g. for drain outlets and roof drains (ref: ASCE7-16, ASPE, International Plumbing Code: ASCE, 2017). Drain manufacturers may not provide details such as flow rates and hydraulic head.

- “Roof drainage systems shall be designed in accordance with the provisions of the code that has jurisdiction. The design flow capacity rate of the secondary (overflow) drains (including roof drains and downstream piping) or scuppers, and their resulting hydraulic head (dh) shall not be less than that of the primary drains or scuppers based on a rainfall intensity equal to or greater than the 15-minute duration/100-year return period (frequency) storm. Primary drainage systems shall be designed for a rainfall intensity equal to or greater than the 60-min duration/100-year return period (frequency) storm.” (ASCE7-16 and Chock et al. 2018).
- “The 2015 International Plumbing Code requires the use of the 100-year return period/60-minute duration for the design of both the primary drainage system and the secondary drainage system. However, from a structural engineering standpoint, the critical duration for most roof geometries (the duration which maximises the hydraulic head) is closer to 15 minutes.” (Chock et al. 2018)
- Each portion of a roof shall be designed to sustain the load of all rainwater that will accumulate on it, if the primary drainage system for that portion is blocked, plus the uniform load caused by water that rises above the inlet of the secondary drainage system at its design flow. (ASCE7-16 and Chock et al. 2018).
- “If the secondary drainage systems contain drain lines, such lines and their point of discharge shall be separate from the primary lines. Rain loads shall be based on the total head (static head [ds] plus hydraulic head [dh]) associated with the design flow rate for the specified secondary drains and drainage system. The total head corresponding to the design flow rate for the specified drains shall be based on hydraulic test data.” (Chock et al. 2018)
- “Where a roof drain is installed in a sump pan located below the adjoining roof surface, reductions in hydraulic head and rain load on the adjoining roof surface should only be credited when based on hydraulic analysis from a qualified plumbing engineer.” (ASCE 7-16)
- Ponding instability and ponding load on roof systems: “As water accumulates on roofs, roof deflection allows additional water flows to such areas, and the roof tends to deflect more, allowing a deeper pond to form there. If the structure does not possess enough stiffness to resist this progression, failure by localised overloading may result. Regardless of roof slope, if water is impounded on the roof to reach a secondary drainage system, ponding instability can occur. Where such impounded water situations exist, the bay is considered a susceptible bay.” (ASCE 7-16)
- For existing building stock in a high-risk category, suitable retrofitting and design improvements need to be adopted.
- The buildings in coastal high hazard areas are prone to exposures for coastal flooding, high velocity wave actions, and high winds. Hence, the buildings in such locations should be designed to resist the effects and wind and flood loads acting simultaneously (FEMA, 2018c)

- A useful flood resilience arrangement in certain vulnerable locations (e.g. coastal high hazard areas) can be use of relevant breakaway walls with suitable flood openings in buildings. The breakaway wall is not part of the structural support of the building and this wall is intended through its design and construction to collapse under specific lateral loading forces, without causing damage to the elevated portion of the building or supporting foundation system[3].

5.5 Some examples from international codes, ASCE and FEMA, USA

In this section, some useful extracts from building code requirements and comparisons are compiled from the ASCE standards, International Residential Code (IRC), International Building Code (IBC), and FEMA in the USA, such as the quick reference guide documents of FEMA (2012) and FEMA (2018c).

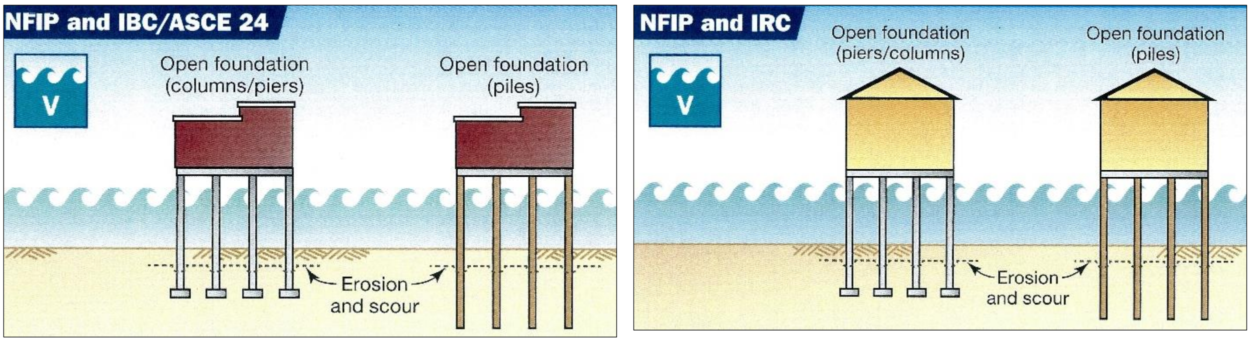


ASCE 24 – American Society of Civil Engineers Standard ASCE/SCI 24-14: Flood Resistant Design and Construction
BFE – Base Flood Elevation for the lowest floor
CAZ – Coastal 'A Zone'
IBC – International Building Code
IRC – International Residential Code
NFIP - National Flood Insurance Program in USA
Zone A – Riverine/ coastal flood prone areas subject to storm surges with velocity waves of less than 3 feet (90 cm approximately)

Figure 3. Building foundation types for flood resilience in Zone A (Figure Source: FEMA, 2018c)

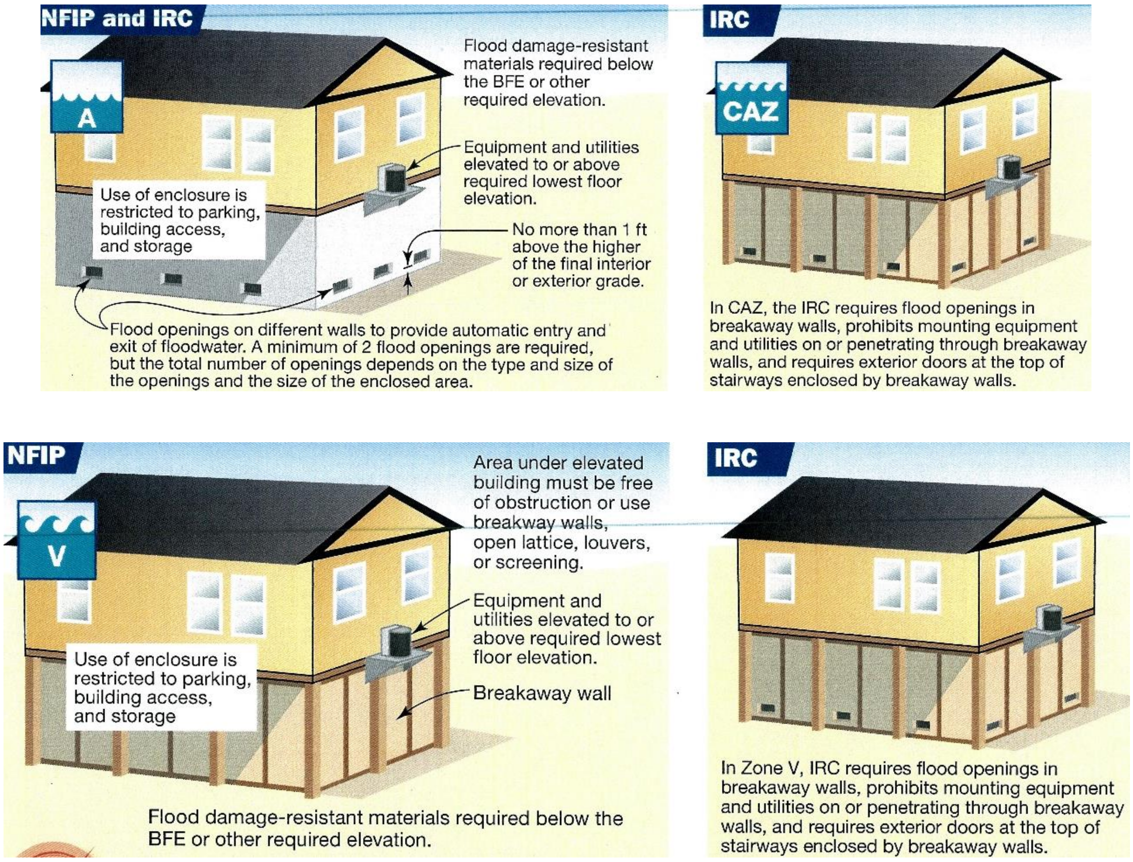
---

[3] https://www.fema.gov/breakaway-wall



ASCE 24 – American Society of Civil Engineers Standard ASCE/SCI 24-14: Flood Resistant Design and Construction
IBC – International Building Code
IRC – International Residential Code
NFIP - National Flood Insurance Program in USA
Zone V – Coastal high hazard areas subject to storm surges with velocity waves of 3 feet (90 cm approximately) or more during the 100-year flood

Figure 4. Building foundation types for flood resilience in Zone V (Figure Source: FEMA, 2018c)



BFE – Base Flood Elevation for the lowest floor
CAZ – Coastal 'A Zone'
IBC – International Building Code
IRC – International Residential Code
NFIP - National Flood Insurance Program in USA
Zone A – Riverine/ coastal flood prone areas subject to storm surges with velocity waves of less than 3 feet (90 cm approximately)
Zone V – Coastal high hazard areas subject to storm surges with velocity waves of 3 feet (90 cm approximately) or more during the 100-year flood

Figure 5. Equipment and enclosures below elevated buildings (Figure Source: FEMA, 2018c)

6 MAINTENANCE FOR FLOOD RESILIENCE

6.1 Complexities and challenges in maintenance

A wide range of factors can contribute to the complexities and challenges in maintenance for flood resilience. Some examples include:

- Type of material and construction; e.g. weather-board, brick, brick veneer, metal (such as steel), concrete, hazardous material (such as asbestos), hollow walls, double walls.
- Age of the building.
- Design and size; e.g. foundation type, single/double storey, buildings with cellars/basements, ducted heating/cooling.
- Attached equipment, annexures and non-structural/utility fixtures; e.g. complex electrical and mechanical installations, solar panels, light-weight sheds, garden structures, swimming pools and equipment.
- Regulatory regimes and governance; e.g. at original approval, major changes and retrofits.
- Condition of the building; e.g. the effects of prior/current defects and problems (structural/non-structural), damage (man-made/natural disasters), repairs and alterations.
- Current and intended purpose; e.g. residential/non-residential, aged care facility, school, heritage building.
- Documentation; e.g. extent (period), coverage of details, format (paper/digital), accuracy and quality, availability (such as open/confidential, comprehensive/partial).
- Location and exposure potential; e.g. high hazard flood zone, elevation of ground floor/lowest floor, building material/components below flood level.
- Social factors; e.g. current occupancy, neighbourhood disturbances, commuting requirements.
- Economic factors; e.g. costs, cost versus benefits, lifecycle costs and remaining life.
- Safety and health aspects.
- Environmental and energy/resource aspects.
- Materials, including spares; e.g. fit-for-purpose and compliance, matching with previous materials, cost versus quantity requirements, availability, storage.
- Workforce; availability, cost, knowledge and skills, workmanship, integrity/ trust.

6.2 Safety evaluation and checklists to repair flood damage in buildings

The extent of flood damage in buildings can vary according to exposure and condition aspects such as the severity and duration of a flood, flood resistance/resilience/protection arrangements, building type and condition. Repairing and maintaining flood-damaged buildings is generally a reactive maintenance strategy. Safety evaluation is a critical requirement before repairing flood damage.

An array of inspection contexts and checklist items can be consolidated from various reports and practices such as ATC (2004), Bravery et al. (2003), BRE (1997 a, b, c, d), and BRE (2006). Such checklist items would be relevant to some proactive maintenance in some cases; e.g. precedence/ recurrent flooding or other related hazards such as water/ moisture ingress from high winds and cyclones.

Some example checklist items and sample points for basic reference are:

- Checklist for immediate action at initial stages should cover structural damage, electrical and mechanical systems/appliances, gas systems/appliances, and drainage systems and sewer/plumbing appliances.
- Checklist for repairing flood damage to ground floors and underground basements/storage should cover cleaning, dewatering, drying, dampness, ventilation, heating/air-conditioning, fungal/bacterial/other microbes, decay/deteriorations, corrosive/hazardous chemicals, structural integrity and stability, material compatibility and availability aspects as well as electrical and mechanical systems/appliances, gas systems/appliances, and drain systems and sewer/plumbing appliances.
- Checklist for repairing foundations should cover excavation, dewatering, drying, decay/deteriorations, corrosive/hazardous chemicals, structural integrity and stability, soil condition and geotechnical stability, material compatibility and availability aspects as well as drain systems and embedded subsurface building service installations (e.g. electric lines and gas connections).
- Checklist for repairing walls and roofs should cover cleaning, dewatering/drying, dampness, ventilation, fungal/bacterial/other microbes, decay/deteriorations, corrosive/hazardous chemicals, structural integrity and stability, material compatibility and availability aspects.
- Checklist for repairing building services and finishes should cover cleaning, drying, ventilation, electrical safety, fungal/bacterial/other microbes, decay/deteriorations, corrosive/hazardous chemicals, suitability and connectivity, functionality, compatibility and availability aspects.

6.3 Routine inspection and maintenance for flood resilience of buildings

The literature review, brainstorming discussions and consultations with various industry partners and stakeholders associated with this research revealed the following key points relevant for routine maintenance of buildings to withstand flood vulnerabilities:

- Routine inspection and maintenance for flood resilience of buildings could be a shared responsibility at appropriate levels relevant to all related parties.
- Developing maintenance manuals for flood resilience of buildings and a library/knowledge portal of maintenance checklists would be useful.
- Routine maintenance could target value procurements with performance specifications.
- Standardisation and certification of flood resilience materials, as well as special flood protection products, would enhance the reliability of flood resilience maintenance as well as the effectiveness of inspections auditing compliances.
- Education and training across the maintenance supply chain (e.g. repairers) is needed.

6.4 Predictive maintenance and smart integration with intelligent systems

Predictive maintenance can yield the best value and sustainable resilience of buildings against natural hazards such as floods. However, developing predictive maintenance systems for practical use requires significant quality datasets of independent and dependent parameters and variables of building stock maintenance. The architecture and constructs for predictive models can include artificial neural networks and multinomial logistic regressions. It would be useful to link predictive models with integrated databases of building assets with 'as built' information, condition assessment (periodical and post-flood) and cost data (maintenance, repair/retrofit, lifecycle). The maintenance decisions for flood hazards need to be rationalised through integration of building information modelling (BIM), discrete and real-time monitoring frameworks, advanced data analytics and artificial intelligence (AI) including machine learning and deep learning systems.

6.5 Retrofitting to enhance flood resilience of buildings

FEMA (2014) provides guidance for following six retrofitting approaches to enhance the resilience of buildings against flood risks:

1. Elevation – i.e. elevating the building so that the lowest floor is not below the regulated flood level
2. Relocation – i.e. moving the building to suitable higher ground so as to avoid/reduce the flooding exposure

3. Demolition – i.e. tearing down the damaged building and either rebuilding it better (e.g. resilient design, materials) at the same site or building in a new safer location
4. Wet flood proofing – i.e. making the critical parts of the building resilient to flood damage and allowing floodwaters to pass through the building during flooding
5. Dry flood proofing – i.e. sealing the building to prevent entry of floodwaters
6. Barrier systems – i.e. building a floodwall/levee around the building to restrain floodwaters so as to avoid/reduce the damage and deterioration from flood impacts

6.6 Build back better approach for maintenance and sustainable resilience

The 'build back better' for sustainable resilience concept of the United Nations Office for Disaster Risk Reduction (UNISDR, 2017) could be suitably integrated into maintenance operations, especially for major repair/renovation/retrofit/reconstruction of buildings or key components. All post-flood building inspections and repair activities could look for such opportunities.

Some examples of 'build back better' are:

- Elevate vulnerable utilities/equipment above critical datum; e.g. top of platform of equipment is at or above the higher of 'Base Flood Elevation' (BFE) + 1 feet or 'Design Flood Elevation' (DFE) as per ASCE 24-14/
- Avoid mounting equipment and utilities on or penetrating through breakaway walls and provide exterior doors at the top of stairways enclosed by breakaway walls.
- Use flood damage-resistant materials below the BFE.
- As per FEMA (2018c), tanks that serve buildings in Zone V (i.e. Coastal high hazard areas subject to storm surges with velocity waves of 3 feet (90 cm approximately) or more during the 100-year flood) need to be elevated on platforms or installed underground and designed and anchored to account for buoyancy forces, taking into consideration of flood erosion and scour.
- As per International Building Code and ASCE 24-14, elevators are permitted below BFE and elevator shafts are not required to break away or have flood openings; foundation designs must account for flood loads acting on elevators and non-breakaway shaft walls (FEMA 2018c).
- According to FEMA P-348, suitably protect the building utility systems from flood damage (FEMA, 2017c).
- Consider useful guidance in FEMA (2011a) for using flood damage resistant materials and suitable flood risk products in FEMA (2018a).
- Introduce and maintain soak-away designs; e.g. as suggested in BRE Digest DG365 (Garvin, 2016) and enrich a flood resilient built environment (Garvin, 2014).

7 RECOMMENDATIONS

Key recommendations derived from this research into flood resilience of buildings are:

i. All properties (including buildings and landscaping) in flood prone areas should be maintained through continuous monitoring and routine maintenance of critical components.
ii. Maintenance checklists of critical components for the properties should be developed. These need to be integrated with appropriate databases and systems for routine/continuous condition monitoring and maintenance decisions for flood resilience. The checklist should cover all building structural elements (e.g. foundations, floors, walls and roofs), finishes, utilities and non-structural fixtures (e.g. drains, gutters, plumbing and electrics) and landscape architecture within the property.
iii. Strict regulatory controls for building permits and 'mature' governance of maintenance for flood resilience need to be developed.
iv. All new designs should include responsible design for maintainability embracing flood resistance and/ or flood resilience aspects. In addition, responsive construction/ maintenance should be considered, embracing relevant flood resilient technologies and materials in new constructions and retrofitting of existing ones for resilience.
v. Flood resilient planning agendas should be developed for new development and maintaining existing building assets.
vi. A 'smart' systems approach with development of maintenance manuals, smart systems and integrated databases linked with Building Information and lifecycle cost-based predictive/ decision-support models is required for futureproof resilience for flood vulnerabilities.
vii. As a non-mandatory arrangement for foolproof flood resilience, certifications for the maintenance supply chain and flood resilience products/materials could be considered.

7.1 Suggestions for implementation of the recommendations

A generic set of maintenance checklists of critical components could be compiled from information (including references) presented in this Part 3 report. Specific checklists are required for each building category and these lists need to be updated as appropriate. These checklists could be added to the maintenance manuals for individual buildings and the maintenance schedule.

Consultations with government departments, research institutions, stakeholders and professional bodies are required for the recommendations related to regulatory, governance and non-mandatory agenda. These include flood resilience planning, responsive maintenance and maintenance responsibilities, supply chain certification, futureproof resilience, and the 'Framework for specifying building maintenance' as described in Part 1 of the report (Pham and Palaneeswaran, 2018).

Further research and development along with benchmarking international developments is required; for example for futureproofing sustainable flood resilience such as through a BIM-integrated intelligent system for maintenance and lifecycle cost-based flood resistance/resilience decisions.

Figure 6 illustrates considerations in enhancing building resilience to flood risks.

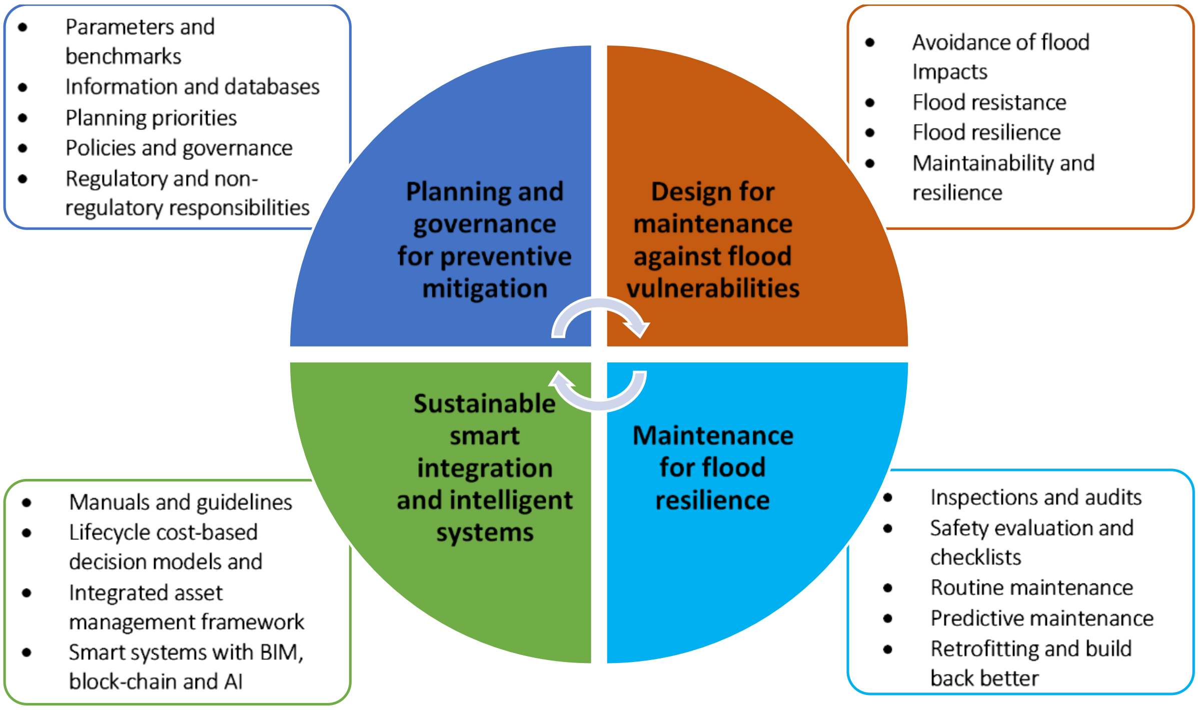


Figure 6. Enhancing building resilience to flood risks

8 REFERENCES

ABCB (2012). Construction of Buildings in Flood Hazard Areas, Version 2012-2, Australian Building Codes Board (ABCB), Australia.

ABCB (2016). National Construction Code 2016 – Volume Two: Building Code of Australia – Class 1 and Class 10 Buildings, March 2016, Australian Building Codes Board (ABCB), Australia.

ABCB (2017). Understanding the NCC – Building Classifications, Australian Building Codes Board (ABCB), Australia.

ABCB (2018). National Construction Code 2016 – Volume One Amendment 1: Building Code of Australia – Class 2 to Class 9 Buildings, Second Edition: March 2018, Australian Building Codes Board (ABCB), Australia.

AIDR (2017). Managing the floodplain: A guide book to best practice in flood risk management in Australia. Australian Institute for Disaster Resilience (AIDR), Melbourne, Australia.

ASCE (2014). Flood Resistant Design and Construction, ASCE Standard ASCE/SCI 24-14. American Society of Civil Engineers (ASCE), USA.

ASCE (2017). Minimum Design Loads and Associated Criteria for Buildings and Other Structures, ASCE Standard ASCE/SCI 7-16. American Society of Civil Engineers (ASCE), USA.

ATC (2004). Field Manual: Safety Evaluation of Buildings after Windstorms and Floods, ATC-45, Applied Technology Council, California, USA.

BNHCRC (2017). A summary of workshop outputs supporting the statement on national research priorities for natural hazards emergency management – Issues, priorities, directions. Bushfire and Natural Hazard Cooperative Research Centre (BNHCRC), Australia.

Bonfield, P. (2016). The Property Flood Resilient Action Plan – An action plan to enable better uptake of resilience measures for properties at high flood risk. Department of Environment, Food and Rural Affairs, UK.

Bravery, A.F., Berry, R.W., Carey, J.K., Cooper, D.E. (2003). Recognising wood rot and insect damage in buildings, *BR 453*, British Research Establishment, UK.

BRE (1997a). Repairing Flood Damage: Immediate Action, *Good Repair Guide 11 – Part 1*, British Research Establishment, UK.

BRE (1997b). Repairing Flood Damage: Ground Floors and Basements, *Good Repair Guide 11 – Part 2*, British Research Establishment, UK.

BRE (1997c). Repairing Flood Damage: Foundations and Walls, *Good Repair Guide 11 – Part 3*, British Research Establishment, UK.

BRE (1997d). Repairing Flood Damage: Services, secondary elements, finishes, fittings, *Good Repair Guide 11 – Part 4*, British Research Establishment, UK.

BTE (2001). Bureau of Transport Economics, Economic Costs of Natural Disasters in Australia, *Report 103*, Canberra, 2001.

CCCA (2011). Houses for flood-prone areas. Briefing (18 June 2011). Cement, Concrete & Aggregates Australia (CCCA), Australia.

Chock, G., Ghosh, S.K., O'Rourke, M., and Stafford, T.E. 2018. Significant changes to the minimum design load provisions of ASCE 7-16, ASCE Press.

COAG (2011). National strategy for disaster resilience. Council of Australian Governments (COAG), Australia.

CSIRO (2000). Floodplain management in Australia: Best practice principles and guidelines, SCARM Report 73, Scientific Committee on Agriculture and Resource Management (SCARM), CSIRO Publishing, Australia.

DCLG (2007). Improving the flood performance of new buildings – Flood resilient construction, Department for Communities and Local Government, London, UK.

Environment Agency (2018). National Flood and Coastal Erosion Risk Management Strategy (Revised): Strategic Environmental Assessment (SEA) Scoping Report, September 2018, Environment Agency, Bristol, UK.

FEMA (2007). Design Guide for Improving Critical Facility Safety from Flooding and High Winds, FEMA 543, Federal Emergency Management Agency, Washington, DC, USA.

FEMA (2010a). Natural Hazards and Sustainability for Residential Buildings, FEMA P-798, Federal Emergency Management Agency, Washington, DC, USA.

FEMA (2010b). Design Guide for Improving School Safety in Earthquakes, Floods, and High Winds, FEMA P-424, Federal Emergency Management Agency, Washington, DC, USA.

FEMA (2011a). Build with flood damage resistant materials: Protecting your property from flooding. Federal Emergency Management Agency, Washington, DC, USA.

FEMA (2011b). Multi-hazard Loss Estimation Methodology Flood Model Hazus®-MH 2.1 Technical Manual. Federal Emergency Management Agency, Washington, DC, USA.

FEMA (2011c). Coastal Construction Manual – Principles, and practices of planning, siting, designing, constructing, and maintaining residential buildings in coastal areas, FEMA P-55 (Fourth Edition). Federal Emergency Management Agency, Washington, DC, USA.

FEMA (2012). Quick Reference Guide: Comparison of Select NFIP and Building Code Requirements for Special Flood Hazard Areas. Federal Emergency Management Agency, Washington, DC, USA.

FEMA (2014). Homeowner's Guide to Retrofitting - Six Ways to Protect Your Home From Flooding, FEMA P-312: 3rd Edition, Federal Emergency Management Agency, Washington, DC, USA.

FEMA (2017a). Flood after fire: The increased risk. Fact Sheet, October 2017. Federal Emergency Management Agency, Washington, DC, USA.

FEMA (2017b). Flood after fire toolkit, December 2017.

FEMA (2017c). Protecting Building Utility Systems from Flood Damage – Principles and Practices for the Design and Construction of Flood Resistant Building Utility Systems, FEMA P-348, Edition 2, Federal Emergency Management Agency, Washington, DC, USA.

FEMA (2018a). Flood Risk Products – Using flood risk products in hazard mitigation plans. Federal Emergency Management Agency, Washington, DC, USA.

FEMA (2018b). Understanding Mudflow and the NFIP. Federal Emergency Management Agency, Washington, DC, USA.

FEMA (2018c). Comparison of select NFIP and 2018 I-Code requirements for special flood hazard areas – Quick Reference Guide, Federal Emergency Management Agency, Washington, DC, USA.

BRE (2006). Repairing flooded buildings – An insurance industry guide to investigation and repair. Flood Repairs Forum, BRE Press, British Research Establishment, UK.

Garvin, S. (2012a). Flood-resilient building – Part 1: Legislation, planning, flood-risk assessment and performance of buildings. BRE Digest: DG 523 (Part 1), IHS.BRE Press, British Research Establishment, UK.

Garvin, S. (2012b). Flood-resilient building – Part 2: Building in flood-risk areas and designing flood-resilient buildings. BRE Digest: DG 523 (Part 2), IHS.BRE Press, British Research Establishment, UK.

Garvin, S. (2014). BRE White Paper - A Future Flood Resilient Built Environment, BRE Trust, British Research Establishment, UK

Garvin, S. and Hunter, K. (2014). Applying flood resilience technologies. BRE report: GC 84, BRE Trust, British Research Establishment, UK.

Garvin, S.L. (2016). Soakaway design. BRE Digest DG 365, British Research Establishment, UK.

HC (2017a). Future flood prevention: Government's response to the Committee's Second Report of Session 2016-17. House of Commons (HC) – Environment, Food and Rural Affairs Committee, UK.

HC (2017b). Post-legislative scrutiny: Flood and Water Management Act 2010. House of Commons (HC) – Environment, Food and Rural Affairs Committee, UK.

HM Government (2016). National Flood Resilence Review. HM Government, UK.

International Codes Council (2014). Reducing Flood Losses Through the International Codes.

Melbourne Water (2007). Guidelines for development in flood-prone areas. Melbourne Water, Victoria, Australia. Available at: https://www.melbournewater.com.au/media/580/download

National Infrastructure Commission (2018). National Infrastructure Assessment. July 2018. National Infrastructure Commission, UK.

National Institute of Building Sciences (2017). Natural Hazard Mitigation Saves: 2017 Interim Report, National Institute of Building Sciences, Washington, USA.

New South Wales Government (2007). Reducing vulnerability of buildings to flood damage – Guidance on building in flood prone areas. Department of Natural Resources, New South Wales Government, Australia.

Pham, L., Palaneeswaran, E. and Stewart, R. (2018). Knowing maintenance vulnerabilities to enhance building resilience, Proceedings of the 7th International Conference on Building Resilience: Using scientific knowledge to inform policy and practice in disaster risk reduction (ICBR2017), Bangkok, Thailand, 27-29 November 2017, Procedia Engineering, Elsevier, 212, 1273-1278. Available at: https://doi.org/10.1016/j.proeng.2018.01.164

Pham, L, and Palaneeswaran, E. (2018). Overview of losses from extreme events and building maintenance recommendations, Part 1 of Final Research Report – SBEnrc Project P1.53: Resilent Buildings – Informing Maintenance for Long-term Sustainability. Available at: https://sbenrc.com.au/research-programs/1-53/

Queensland Government (2017). Queensland Strategy for Disaster Resilience: Making Queensland the most disaster resilient state in Australia.

Queensland Reconstruction Authority (2012). Planning for stronger, more resilient floodplains. Queensland Reconstruction Authority, Queensland Government, Australia.

UNISDR (2017). Build Back Better – in recovery, rehabilitation and reconstruction. United Nations Office for Disaster Risk Reduction. https://www.unisdr.org