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Flood Hazard

WRL Technical Report 2014/07
September 2014

By G P Smith, E K Davey and R J Cox

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1. Introduction

Emergency Management Australia has recently released *AEM Handbook 7 - Managing the floodplain: a guide to best practice in flood risk management in Australia* (AEMI, 2013). The report discusses best practice for floodplain management, and introduces and describes the need for quantifying flood hazard as part of the floodplain management process.

Flood hazard assessment is a key input to the understanding of risk. In the floodplain management process, flood hazard mapping assists with identifying the relative degree of flood hazard on a floodplain without the need to specifically understand what is at risk. Hazard mapping also feeds into constraints mapping for floodplain areas.

While AEM Handbook 7 introduces flood hazard as a concept and makes definitions of flood hazard, it does not provide detailed advice on how to quantify flood hazard.

It is the intention of the National Flood Risk Advisory Group (NFRAG) Committee that AEM Handbook 7 be supported by several technical guidelines, one of which will be a guideline on flood hazard quantification and classification. This guideline will build on the advice provided in Appendix J of the now superseded SCARM Report 73 - *Floodplain management in Australia: best practice principles and guidelines* (SCARM, 2000).

This report provides background information that may form the basis of a technical guideline on assessing flood hazard. The report is broken down into the following sections following this introduction:

Section 2 provides a review of SCARM (2000) from the perspective of flood hazard quantification and classification with a focus on Appendix J of that document.

Section 3 summarises important issues forthcoming from the SCARM (2000) review.

Section 4 describes the findings of an international literature review of flood hazard.

Section 5 provides a description of recommended updates to flood hazard threshold curves.

Section 6 describes methods for the quantification and classification of flood hazard based on the information collated in previous sections of the report.

Section 7 summarises the report findings and makes recommendations for a technical guideline to support AEM Handbook 7.

2. SCARM Report 73 - Review

SCARM Report 73 - *Floodplain management in Australia: best practice principles and guidelines* (SCARM, 2000) provides principles and guidelines for floodplain management in Australia. The document had its genesis from a need independently identified by both the Floodplain Management Working Group of the Agriculture and Resource Management Council of Australia and New Zealand and Emergency Management Australia.

SCARM Report 73 aims to provide a set of best practice principles and guidelines for the management of the risks associated with flooding across Australia's floodplains. However, this document, published in 2000, has since become outdated. A new document, *AEM Handbook 7 - Managing the floodplain: a guide to best practice in flood risk management in Australia* (AEMI, 2013) updates SCARM Report 73, as well as the Emergency Management Australia, Manual 19: *Managing the Floodplain* (EMA, 1999).

Amongst its broad description of floodplain management practice, SCARM Report 73 identifies the management of flood hazard as central to the floodplain management process and "*the most critical aspect of floodplain management*". In this sense, a cornerstone of floodplain management identified in SCARM Report 73 is the aim to minimise the exposure of the community to hazardous flood conditions. Management of flood hazard in this context necessarily requires it to be quantified. SCARM Report 73 provides advice on hazard quantification methods in Appendix J.

Flood Hazard is defined in SCARM Report 73 as "*potential loss of life, injury and economic loss caused by future flood events. The degree of hazard varies with the severity of flooding and is affected by flood behaviour (extent, depth, velocity, duration and rate of rise of floodwaters), topography, population at risk and emergency management".* This definition remains relevant as the concept of flood hazard has not changed or evolved significantly since SCARM Report 73 was published.

2.1 SCARM Report 73 Appendix J: Flood Hazard

The following discussion summarises and makes comment on Appendix J of SCARM Report 73 (2000). A summary of the key points of each report section is provided.

SCARM Report 73 (2000) groups the hazard and disruption caused by flooding into four broad categories:

- Flood behaviour (i.e. severity, depth, velocity, rate of rise, duration);
- Topography (i.e. evacuation routes, islands);
- Population at risk (i.e. number of people, number of developments, type of land use, flood awareness); and
- Emergency management (i.e. flood forecasting, flood warning, flood response plans, evacuation plans, recovery plans).

Flood severity is highlighted in Appendix J as the principle determinant of hazard. However, no recommendations are made for the appropriate design flood that should be considered for flood hazard assessment, nor is a recommendation made as to who is responsible for deciding the design flood probabilities for flood hazard assessment. There are numerous documented floodplains (HNFMSC, 2006a) where flood hazard at a specific location can increase greatly between floods of differing severity, for example between the 1% and 0.5% annual exceedance probability (AEP) flood events.

Contemporary practice when considering the floodplain risk considers a range of flood events beyond the defined flood event (DFE) up to the probable maximum flood (PMF) or another extreme event so that the residual risk exposure can be identified. The residual risk to a community and the likely flood hazard conditions in more extreme events is an important consideration for flood emergency planners, land use planners and flood risk managers.

Appendix J of SCARM Report 73 makes several definitive statements regarding the risk to life in flood events, highlighting that these can be largely defined by the depth and velocity of floodwaters. These statements include:

- Wading by able-bodied adults becomes difficult and dangerous when the depth of still water exceeds 1.2 m, when the velocity of shallow water exceeds 0.8 m/s, and for various combinations of depth and velocity between these limits.
- In assessing the safety of wading, factors other than depth and velocity need to be taken into account such as evenness of the ground surface or presence of depressions, potholes, fences or major stormwater drains.
- Small, light, low motor vehicles crossing rapidly flowing causeways can become unstable when water depths exceed 0.3 m. Evacuation by larger, higher sedans is generally only possible and safe when water depths are less than 0.4 m.
- At velocities in excess of 2 m/s, the stability of foundations and poles can be affected by scour. As grass and earth surfaces begin to erode, scour holes can develop.
- At depths in excess of 2 m, lightly framed buildings can be damaged by water pressure, flotation and debris impact, even at low velocities.
- Depth of flooding—and hence overall degree of flood damage—can be increased by obstructions to floodwater movement.

Flood hazard thresholds described in these statements above relate hazard levels to the vulnerability of people, vehicles and structures when exposed to flooding. These thresholds, provided as point thresholds, are somewhat limited in their scope. Recent research and guidance, in particular that conducted for the Australian Rainfall and Runoff Revision Project 10 (e.g. Cox *et al.*, 2010; Shand *et al.*, 2011), allow some of these values to be revised and expanded. A literature review of recent research with discussion of recommended revisions to flood hazard thresholds regarding people, vehicle and building stability is provided in Section 4.

SCARM Report 73 Appendix J highlights that situations where floodwaters rise rapidly are potentially far more dangerous than situations where flood levels increase more gradually. Conditions resulting in 'flash floods' have been regularly discussed in recent times, particularly following the 2011 Lockyer Valley and Toowoomba Floods where there were 19 lives lost. The flooding in the Lockyer Valley was an extreme event (estimates suggest the peak flows and levels of the January 2011 flood event lie above the 0.2% (1:500) AEP event and just below the 0.05% (1:2000) AEP event (Rogencamp and Barton, 2012)). At the flood gauge at Helidon water levels rose from 5 m at 2:20 pm to 13 m at 2:50 pm at which time, the gauge failed, representing a rise of 8 m in 30 minutes or equivalent to 1 m every 4 minutes (Rogencamp and Barton, 2012). This event was a stark reminder of the vulnerability of people exposed to flood waters with little or no warning.

Comment is made in SCARM Report 73 Appendix J regarding the duration of flooding. The commentary highlights the importance of appropriate education of the community and preparedness of individuals for potential flood conditions at their properties, as well as highlighting some potential issues with the concept of 'shelter-in-place' during flood events. Further discussion regarding the potential issues associated with building stability and sheltering in place during flood events is provided in Section 4.3 of this report.

SCARM Report 73 Appendix J outlines a series of issues associated with evacuation. Again, the concepts presented remain relevant. Further discussion of evacuation issues, and associated emergency planning constraints, are discussed in Section 3. It is important to note that not only are the flood hazard thresholds different for people, vehicles and building stability, but also that the flood hazard can change substantially during different stages of floods. Subsequently, evacuation planning must consider the flood conditions, and associated hazard at all stages throughout the event to develop the most appropriate evacuation response.

Several important points about effective flood access are outlined in SCARM Report 73 Appendix J. When relying on vehicular evacuation during a flood, it is important there is 'effective access' i.e. a high-level exit route that remains trafficable for a sufficient time to evacuate. The draft Flood Evacuation Capacity Assessment Guidance prepared for NSW State Emergency Service (NSW SES) (Molino Stewart (2013b)) provides a method for quantifying evacuation capacity. A thorough discussion is provided in the AEM Handbook 7 (AEMI, 2013) about isolation during flood events, including the concept of high and low flood islands (Figure 2-1).

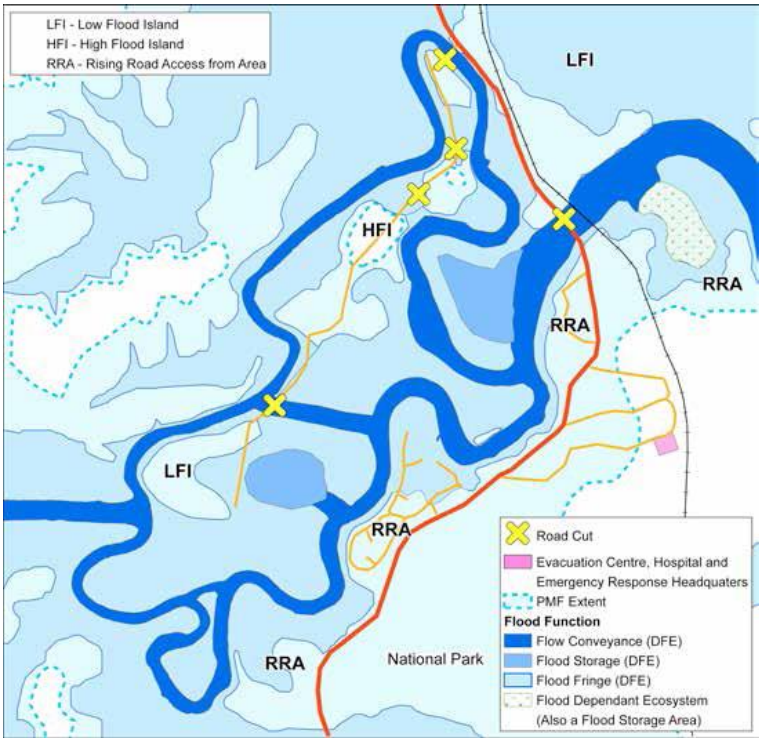


Figure 2-1: Areas with different emergency response categories (Source: AEMI, 2013)

Importantly, SCARM Report 73 Appendix J highlights that the degree of hazard and social disruption can vary with the size of the population at risk, and that land use affects flood hazard. For example, there are considerably greater difficulties evacuating a hospital or retirement village than an industrial area. Consideration when planning such developments within a floodplain area should address the following questions:

- Is the building likely to be isolated for any duration of time during the flood event?
- Is the building going to be in an area of unacceptable hazard during the flood event?
- Is it possible to evacuate the building within the required time frame?
- If the building is not in an area of unacceptable hazard, but is to be isolated, are the appropriate backup systems in place to enable the survival of the residents?

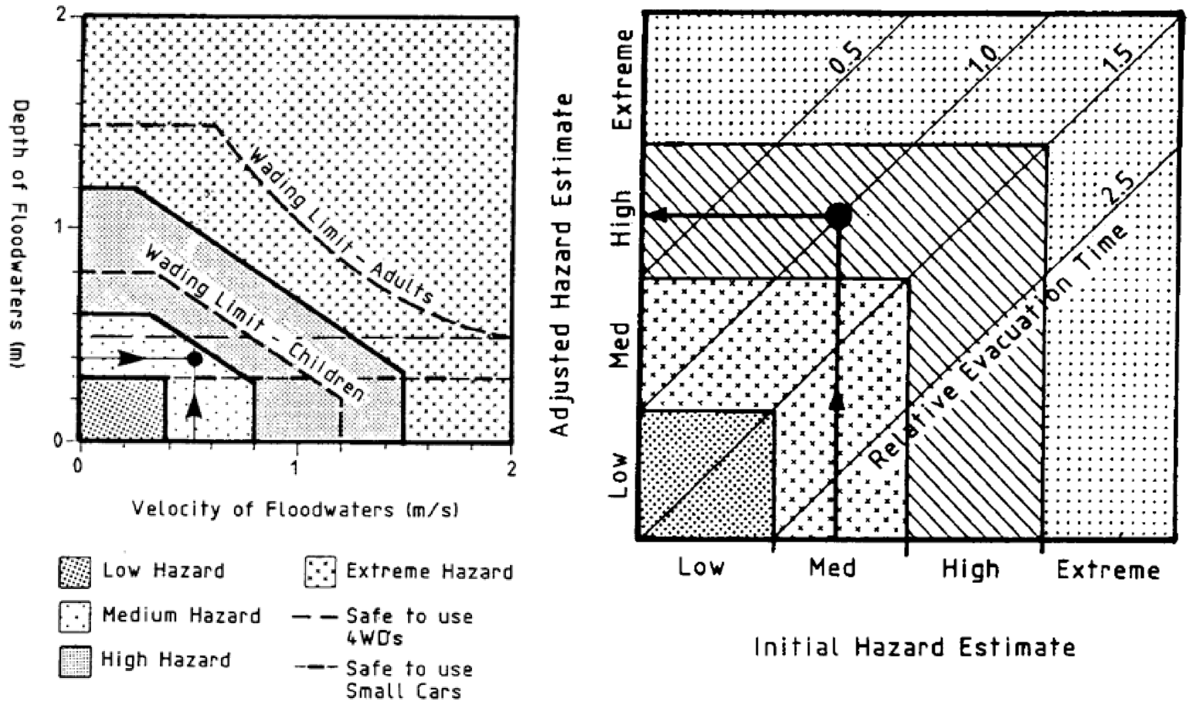
Part of the challenge of quantifying flood hazard is to set meaningful thresholds for the levels of 'unacceptable hazard' referred to in the questions above. More discussion on flood hazard thresholds is provided in Sections 4 and 5.

It has been observed that the Australian reaction to disaster situations is not unlike that of the rest of the world. Many Australians do not appear to perceive the risk associated with natural disasters, although official warnings are issued, and do not follow risk management guidelines and advice (Dominey-Howes and Goff, 2010) often placing themselves in hazardous situations that continue to result in fatalities.

Somewhat related to the necessary considerations for flood awareness is warning time. Risk to life during flood events can be substantially reduced by evacuation if adequate time is available to evacuate. As highlighted in SCARM Report 73 Appendix J, available warning time is largely determined by catchment characteristics, such as catchment size and flood water rate of rise. In larger catchments, generally, there is a longer warning time and flood warnings can be based on correlated rates of rise and peak water levels at upstream gauges. Unfortunately, flood warning for small catchments may need to be based on predictions of likely rainfall made before the rainfall actually occurs, using techniques such as rainfall radar and predictive modelling. However, in some cases, no specific warning can be given and only general warnings for severe weather in areas are possible. Effective warning time, or actual time available for evacuation, is always less than the available warning time, due to the time needed to alert people to the incoming flood, and commence evacuation.

SCARM Report 73 Appendix J discusses the degree of hazard, highlighting that it varies across the floodplain in response to factors such as flood severity, floodwater depth and velocity, rate of rise of floodwater, duration of flooding and evacuation problems. The report notes that as part of the floodplain management process it is necessary to determine hazard, to determine the appropriateness, or otherwise, of various land uses.

Four degrees of hazard are recognised in Appendix J: low, medium, high and extreme. These different hazard categories are related to the relative difficulty of evacuation, including commentary relating the time that an evacuation route remains open relative to the necessary time to evacuate. A discussion of estimation of hazard, as well as two 'hazard graphs' (Figure 2-2), are presented in SCARM Report 73 Section J.3. The flood hazard thresholds described in Figure 2-2 below rate flow behaviour in comparison to stability thresholds for people wading and vehicles driving through floodwaters.



(a) Estimation of Hazard Along Evacuation Routes

(b) Effect of relative evacuation time on hazard rating

Figure 2-2: Hazard Graphs (Source: SCARM, 2000)

The quantification of flood hazard and classification of hazard levels by means of hazard thresholds is a key point that warrants review and revision in any new guideline. Flood hazard varies considerably for people, vehicles and building stability. The application of stability thresholds in a floodplain management context might also need to vary depending on whether the thresholds are being used in consideration of land-use planning or in an emergency planning context. Following review of these aspects, a series of recommended hazard threshold curves is presented in Section 5, developed from the literature review outlined in Section 4. A discussion of different aspects of flood hazard related to timing considerations, particularly for evacuation, is provided in Section 3.

2.2 AEM Handbook 7

AEM Handbook 7 (AEMI 2013) introduces flood hazard as a concept and makes the following important definitions:

> ***Hazard***
>
> *A source of potential harm or a situation with a potential to cause loss. In relation to this handbook, the hazard is flooding, which has the potential to cause damage to the community.*
>
> ***Flood hazard***
>
> *Potential loss of life, injury and economic loss caused by future flood events. The degree of hazard varies with the severity of flooding and is affected by flood behaviour (extent, depth, velocity, isolation, rate of rise of floodwaters, duration), topography and emergency management.*

Section 2.1 Floods and Hazard of AEM Handbook 7 explains the need to assess flood hazard as a component of flood risk assessment:

> *"Floods create hazardous conditions to which humans are particularly vulnerable. If floodplains were unoccupied and unused, flooding would not create a risk to the community. It is the human interaction with the floodplain and the associated exposure to flood hazard that creates flood risk."*

Further, flood hazard is described in broad terms by the physical danger posed by floodwaters and human interactions with flood flows:

> *"Fast-flowing, shallow water or slow-flowing, deep water can unbalance people and sweep them away. Similarly, floodwaters can result in significant impacts on the built environment. Structures can be undermined, or have their structural and non-structural elements damaged or destroyed by floodwater and debris."*

Section 5.3 Flood Hazard in AEM Handbook 7 identifies the key components of flood hazard as:

- Velocity of Floodwaters;
- Depth of Floodwaters;
- Combination of Velocity and Depth of Floodwaters;
- Isolation During a Flood;
- Effective Warning Time; and
- Rate of Rise of Floodwater;

While AEM Handbook 7 describes the need to quantify the level of, and exposure to, flood hazard, it does not provide direct technical advice on how to undertake this quantification.

This background report summarises technical information that describes the basis for flood hazard assessment. Advice for assessing and quantifying flood hazard will be provided as a supplementary technical guideline to AEM Handbook 7. Information in this report can be used as the basis of this technical guideline.

As a component of flood risk, flood hazard assessment has a role in land use planning, emergency management and flood risk management. The derivation and interpretation of flood hazard for these two cases is discussed further in Section 3.3.

3. Issues forthcoming from the SCARM review

3.1 How flood hazard relates to flood risk

In the context of this review, it is important to consider how flood hazard contributes to flood risk. As illustrated in Figure 3-1, flood risk consists of two key components:

- The likelihood (probability) of flooding; and
- The severity or consequences of flooding.

Figure 3-1: Components of Flood Risk (after McLuckie, 2012)

In this regard, the level of flood hazard is a component of, and contributes to, the flood risk on a floodplain.

The definitions of hazard and flood hazard in AEM Handbook 7 (see Section 2.2) clearly annunciate that flood hazard is independent of the population at risk. The 'population at risk' as a concept relates to flood risk and the translation of a hazard to result in a risk to a community. By way of illustration, a flood with high water depth (> 2 m deep) is hazardous whether people are on the floodplain or not. The flood *risk* comes from exposing people to that hazard.

The vulnerability of a community to flood hazard can be benchmarked against flood thresholds, which meaningfully describe the danger of the flooding to people in the community. These thresholds relate the severity of the flood hazard to the vulnerability of the community and built environment under a given flood exposure. Advice for quantification of flood hazard and the application of flood thresholds is provided in Section 6 of this report.

3.2 Factors influencing hazard

The magnitude of flood hazard can be variously influenced by the following factors:

- Velocity of Floodwaters;
- Depth of Floodwaters;
- Combination of Velocity and Depth of Floodwaters;
- Isolation During a Flood;
- Effective Warning Time; and
- Rate of Rise of Floodwater;

When quantifying and classifying flood hazard, it is important to understand the underlying causes of the hazard level. For example, if the hazard level is classified as 'high' then it is important to understand the key reason that it is high e.g. high depth, high velocity, high velocity and depth in combination, isolation issues, short warning time? If the core reasons that the hazard is high are not well understood, then attempts to modify and lower the hazard level may not be successful.

3.3 Uses of hazard analysis in floodplain management

Hazard analysis can be used to provide valuable information to underpin decision making in three key floodplain management areas; as a benchmark for comparison of structural mitigation options; in land use planning, and in emergency management planning.

3.3.1 Structural mitigation assessment

Structural mitigation options modify flood behaviour in targeted locations. Quantification of flood hazard and the associated changes in risks to the community is an integral part of the assessment of the likely benefits of a proposed mitigation structure. Flood mitigation devices may modify flood hazard levels by:

- Decreasing flood depth;
- Reducing velocity;
- Reducing the degree or duration of isolation;
- Reducing rate of rise of floodwaters;
- Reducing duration

By comparing the degree of flood hazard and the level of flood risk pre and post the application of a structural mitigation option, an assessment of the benefits of the option can be made based upon the reduction in impacts. These types of assessments are usually completed by model analysis of the structural option. They would often accompany and support an economic analysis of the structural option.

While structural flood mitigation options may reduce flood risk in a targeted area of the floodplain, the local improvement in flood risk may cause a negative impact on flood behaviour in other areas of the floodplain. Automated hazard mapping methods of broad areas of the floodplain beyond the local area of the structural option can assist in understanding these changes.

3.3.2 Land use planning

Flood behaviour quantification, including flood hazard analysis, is used to guide land use planning in floodplains. Hazard analysis methods applied for land use planning vary significantly when applied to strategic land use planning, greenfield and brownfield sites.

Strategic Land Use Planning

Section 8 of AEM Handbook 7 describes the role of floodplain management in strategic land use planning. In essence, effective strategic land use planning is about responding to flood risks in a way that minimises future flood consequences. Consideration of flood hazard is therefore important so that development of land is encouraged in areas of low or no flood risk wherever possible. A clear understanding of flood risks early in the strategic land use planning process can help steer development away from areas that are not sustainable due to the likely impacts of the development on flood behaviour and guide land use zonings and development controls that support sustainable development on the floodplain in consideration of the flood risk.

AEM Handbook 7 highlights that flood hazard mapping is useful and important baseline information that can be used to form effective strategic planning instruments and development control plans to manage development on floodplains. Flood hazard mapping feeds directly into the broader constraints mapping process.

Quantification of flood hazard in comparison with specific flood thresholds (See Section 5) can inform zone planning and development control plans for specific areas. AEM Handbook 7 notes that effective strategic planning instruments can successfully address the way land use and development have regard for the flood function within the floodplain, the varying degrees and drivers of flood hazard, and the varying vulnerability of buildings and their occupants.

Greenfield Planning

Greenfield development requires the proposed land development be designed to recognise the existing flood hazard of the site. Greenfield development provides the opportunity to set planning standards, which minimise the flood risk exposure of the new development. Careful accommodation of the site's flood hazard can maximise the benefits of using the floodplain while minimising the risks and consequences of flooding to the community.

In designing and planning greenfield developments, knowledge of the flood hazard conditions, quantified by the key characteristics of the flood behaviour and benchmarked against vulnerability thresholds for the community such as people and vehicle stability is key information to inform the planning process.

A well-designed greenfield development will have land at or above the defined flood event (DFE) level with minimum floor levels above the DFE plus an allowance for freeboard. Land filling may be a viable option in Greenfield developments. Greenfield development designs should also be sympathetic to more extreme floods than the defined flood event. Aspirationally, when flooding of a greenfield development occurs for floods greater than the DFE, inundation of properties and evacuation routes will occur with ample warning. Flood levels will rise with low hazard (i.e. low depth and low velocity) providing ample opportunity for the community to prepare and evacuate if necessary.

Successful, greenfield development can be informed by design principles outlined in guidelines such as the Hawkesbury-Nepean Floodplain Management Steering Committee guideline *Designing Safer Subdivisions: Guidance on Subdivision Design in Flood Prone Areas* (HNFMSC, 2006a). This guideline provides a thorough discussion of key components of land use planning that should be considered in flood-affected areas.

Flood hazard quantification is a key input to subdivision design. Detailed guidelines for subdivision designs are cognisant of existing flood flow paths and designed to minimise changes in flow path location and flow behaviour in flooded zones. Factors necessary for consideration include:

- Lot layouts are flood free during the defined flood event;
- The area is accessible and trafficable during defined flood event conditions; and
- The development is sympathetic to evacuations for floods greater than the defined flood event.

Figure 3-2 displays ways that appropriate land uses can be distributed according to exposure to the full range of flood events. Land use planning conducted in this manner can offer opportunities for safer occupation of the floodplain and reduced damage during flood events.

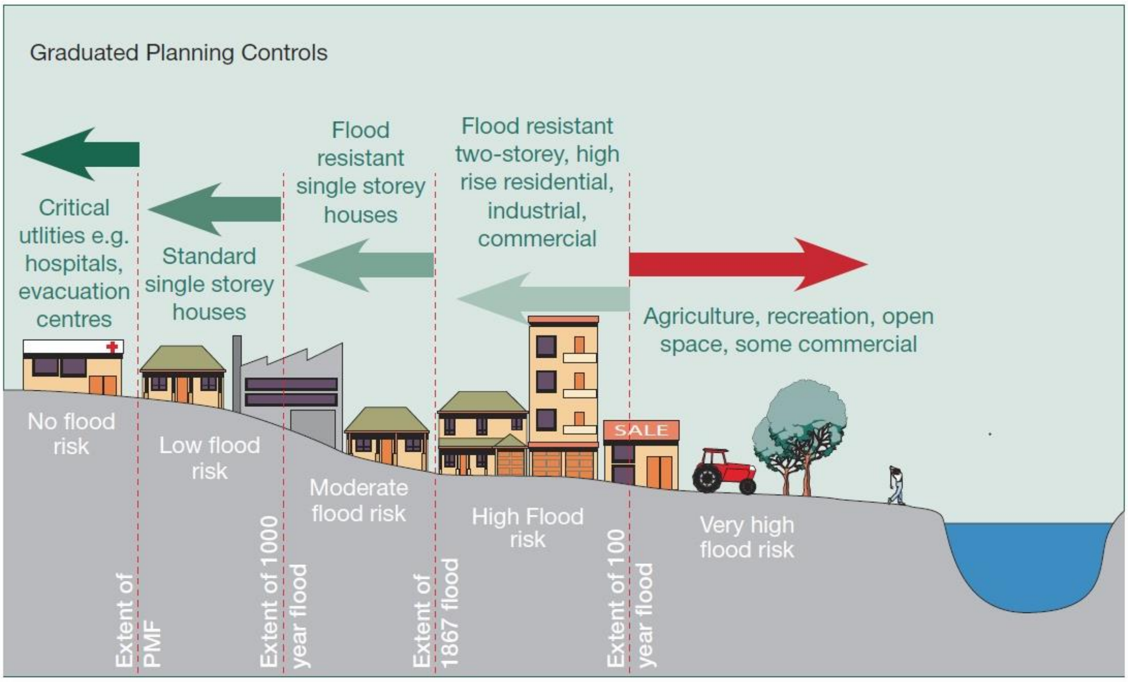


Figure 3-2: Distribution of land uses on the floodplain to reduce risk (Source: HNFMSC, 2006a)

Figure 3-3 presents alternative development layouts to limit the hazard during flood events. In the example below, construction of a cluster development (Figure 3-3, right) provides a substantial reduction in the risk during the flood event. However, the conventional (2) option (Figure 3-3, centre) still provides a reduction in flood risk from the conventional (1) option (Figure 3-3, left).

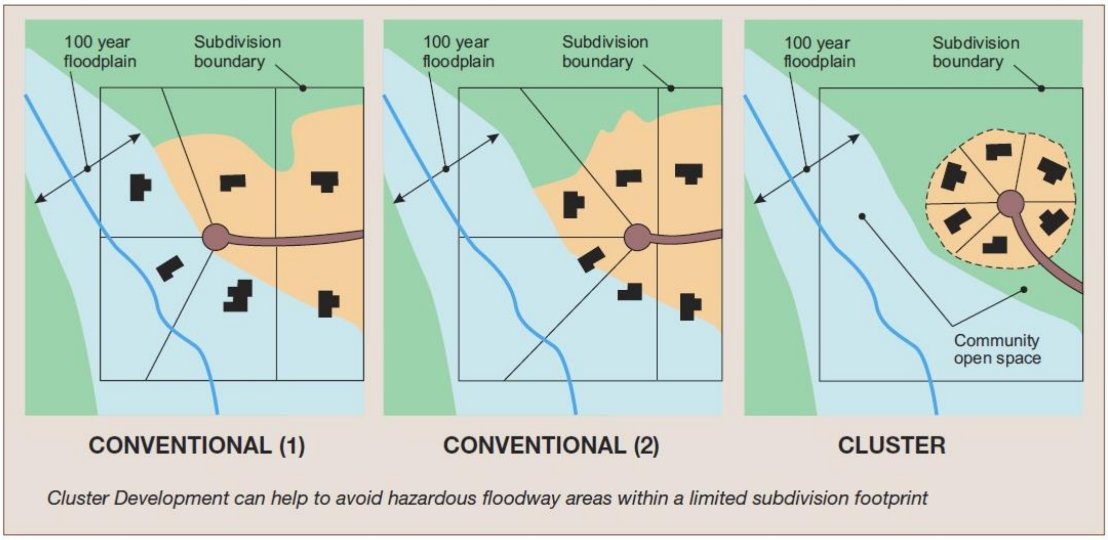


Figure 3-3: Alternative development layouts (Source: HNFMSC, 2006a)

Further, when planning development in flood prone areas consideration of the rate of rise and the direction of inundating floodwaters will reduce flood risk to the community. Figure 3-4 presents two scenarios. In the left option, initial floodwaters entering the subdivision would restrict access to the area, and subsequently limit evacuation options, placing the community at risk. In direct contrast, the right option presents flood free access for evacuation from the subdivision for a much longer period during the flood event.

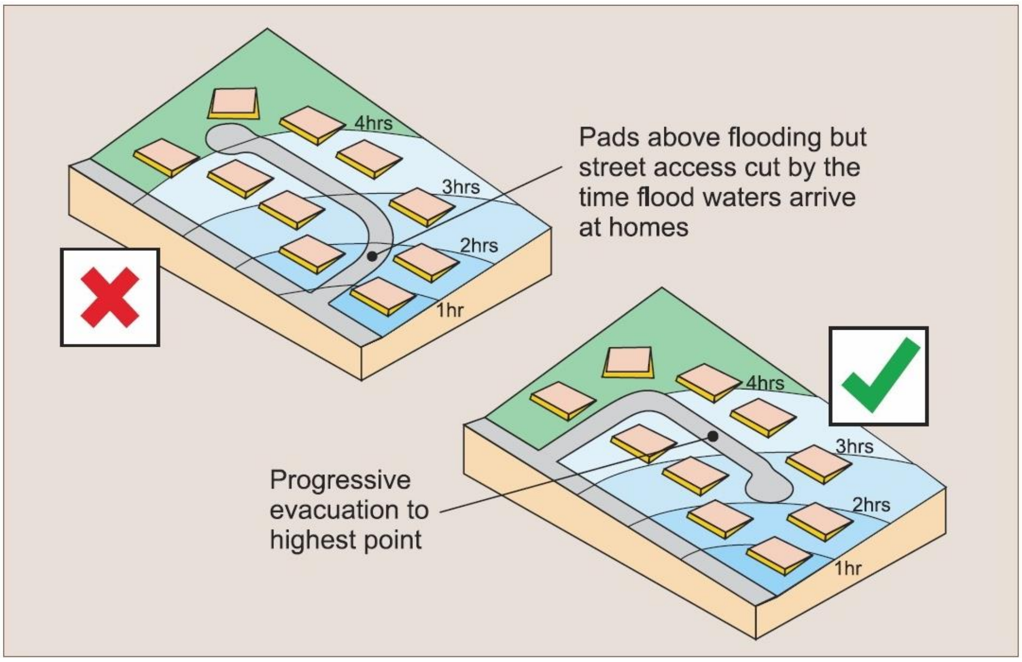
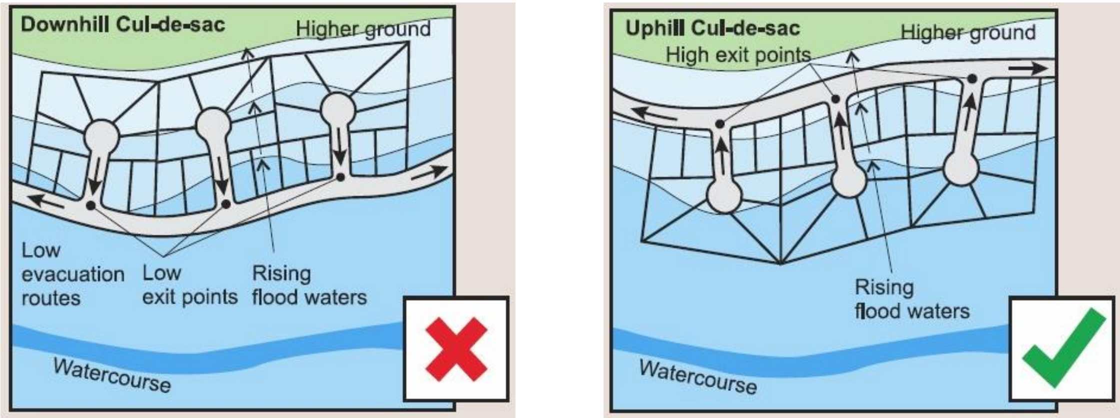


Figure 3-4: Options for road access to subdivisions (Source: HNFMSC, 2006a)

Figure 3-5 illustrates additional advantages and disadvantages with alternative road layouts for development in a greenfield catchment. Option (a) presents a situation in which escape from the flood risk area would be a difficult downhill route, and residents must leave their homes earlier before their evacuation route is cut. This compresses the time available to conduct evacuations, increasing the risk that the evacuation will fail. Further, occupants would be relying on the availability of emergency management resources to co-ordinate the evacuation. In contrast, option (b) presents an easy uphill egress from rising floodwaters, and residents will be prompted to evacuate due to the imminent flooding of their homes, not the closure of the road. Further, the progressive flooding nature of the site allows evacuation to be gradual.



(a) Downhill Cul-de-sac **(b) Uphill Cul-de-sac**

Figure 3-5: Alternative local road layouts (Source: HNFMSC, 2006a)

<u>*Brownfield Planning*</u>
While greenfield planning can proactively deal with and minimise existing flood hazards on a broad scale, brownfield planning to accommodate flooding is regularly a far more reactive process since the flooding issues are often due to inappropriate (with hindsight) development in flood exposed areas, sometimes with high hazard, even for floods smaller than the defined flood event. Brownfield development planning constraints often need to be applied on a property-by-property basis as individual development applications emerge.

While planning for floods in greenfield areas often need only consider flood thresholds for people and vehicle stability on evacuation routes for floods greater than the DFE, building stability thresholds may become relevant for brownfield development.

Brownfield development often involves the difficult process of dealing with development in high hazard flood areas. While structural mitigation is sometimes possible to alleviate flood hazard levels, often the process of dealing with flood hazard involves reviewing and changing land use, development style or scope and development controls in redevelopment. Where flood hazard is extreme on specific properties that meet relevant criteria, redevelopment may not be viable.

In other instances, the only option to address existing floods risks in brownfield areas is effective emergency planning and management. Flood hazard quantification supports emergency planning by identifying priority areas for evacuation, by providing base information to help identify safe flood evacuation routes and by identifying locations, including buildings that are safe refuge during flood events.

3.3.3 Emergency Management

Flood hazard analysis provides important data and information to support Emergency Planning. The need for, and flood constraints on, evacuation is highly dependent on the location on the floodplain. A thorough discussion is provided in the AEM Handbook 7 (AEMI, 2013) including discussion of isolation during flood events examined using the concept of high and low flood islands (Figure 2-1). An assessment of flood behaviour, including warning time and rate of rise of floodwaters is an important aspect of flood hazard quantification for flood emergency planning purposes.

New South Wales State Emergency Service (NSW SES) has developed a flood evacuation capacity assessment guideline (Molino Stewart, 2013b). This guideline provides advice for NSW SES, councils, developers and others to apply the Timeline Evacuation Model to a development or area of interest. This evacuation guideline takes into account the time people take to accept a warning, act upon the warning and travel along an evacuation route including delays that evacuees may face due to incidents along the route. Following the calculation of this "Time Required" for evacuation, a comparison is made between the "Time Required" and an estimation of the "Time Available" derived from information about warning times, flood travel times and flood rates of rise (Molino Stewart, 2013b).

The guideline highlights that where the Time Available exceeds the Time Required there can be greater confidence in the ability of the community to evacuate safely by motor vehicle. In contrast, where the Time Required exceeds the Time Available it is unlikely that everyone will be able to evacuate safely by motor vehicle in all floods (Molino Stewart, 2013b). Subsequently, alternative survival options, such as walking to higher ground or 'shelter-in-place' require consideration or the development scope, scale or configuration may need to be re-thought.

The guideline recognises that evacuation of a development may not necessarily occur in isolation. Other nearby developments may also have to evacuate at the same time, subsequently, provisions are made to estimate how converging evacuation traffic may impact on the ability of communities to evacuate at the same time.

Worked case studies included in the guideline highlight the differences associated with four key events of:

- Evacuation of a simple existing development with minimal traffic convergence (Grafton, NSW);
- Development with multiple flood sources (Schofields, NSW);
- Multiple routes from a proposed urban residential and commercial development interacting with other evacuation traffic (Penrith Lakes, NSW); and
- Evacuating events (North Byron Parklands).

These evacuation scenarios each show different issues and planning outcomes. Evacuation of Grafton is simple, and requires prioritisation of local areas. Proposed development at Schofields shows if there were widespread flooding, evacuation would not happen in a timely fashion for all due to regional traffic convergence. For the flooding of Eastern Creek, no warning would be available and subsequently, "Time Available" is zero. If people did not evacuate immediately upon the floodwaters reaching their property they may be inundated by up to 4 m. A similar issue with regional traffic may also be encountered when evacuating Penrith Lakes.

Evacuating the North Byron Parklands may not be possible at full capacity due to evacuation routes being cut, however it is estimated that all people onsite would be able to reach a flood free zone on foot within 15 minutes, allowing for safety in a flash flood (Molino Stewart, 2013a).

If the time to evacuate is not appropriate, as evacuation may become dangerous due to flood conditions on evacuation routes for people or vehicle stability (further discussed in Sections 4 and 5), it may be necessary for residents to shelter in place. The following issues would require careful consideration before advice for shelter-in-place could be formed:

- *A safe refuge* - Not knowing how high the water may possibly reach is likely to be of major concern. If people are required to shelter-in-place, and are not necessarily in a specified 'flood refuge' above the PMF or a similar extreme event it may cause major anxiety, and leave people trapped. In assessing shelter in place as an option, careful consideration of the range of flood levels from the defined flood event (DFE) to more extreme events up to the PMF is required. In some floodplains, the PMF flood levels may be significantly higher and more hazardous. For example, in some areas of the Hawkesbury-Nepean floodplain in NSW, PMF flood levels are more than 10 m higher than the 1% AEP DFE. If the sheltering area becomes overwhelmed with floodwater, people are likely to drown.
- *Structural adequacy* – further discussed in 4.3 – when advising shelter in place it would be necessary to ensure the specified location was structurally adequate and would survive flood events up to the PMF or another extreme event.
- *Tolerable duration of isolation – "safety of isolation is somewhat subjective and there is no known quantitative basis for determining the tolerable duration of isolation that may result from floods."* (Opper *et al.*, 2011, p.1) Manual 22 of the Australian Emergency Manuals Series, *Flood Response*, suggests that there is no such thing as a 'safe period of isolation', as the isolation of people is not without risk (AEM, 2009). It is highlighted that any individual who experiences a life-threatening event while isolated is at significantly greater risk than a person who experiences the same condition but is not in an isolated position (AEM, 2009). However, AEM (2009) suggests that when it is unsafe to evacuate due to flood waters, it would be safer to shelter-in-place, but does not suggest how long it would be suitable for people to wait before it becomes safe to leave or they will need to be rescued. It is assumed that shelter-in-place is only a solution of last resort in a failed evacuation requiring temporary refuge and rescue if possible.
- *Vulnerability* - Sheltering in place may not be a viable option for the old, very young or immobile. Shelter-in-place without adequate planning and preparedness places additional risks on emergency services and others (e.g. parents, carers) that may come to the rescue. Furthermore, those disabled or sick, may be unable to climb stairs or otherwise to reach the higher areas of the shelter site in order to avoid drowning.
- *Communication and Education* - the Australian public, as a whole need to be able to better respond to warning systems in general and flash flood warnings in particular. Confusion is likely in locations exposed to both flash flooding and riverine flooding or riverine flooding and coastal flooding (storm surge) where there are potentially differing policies or guidelines for response to these different flood drivers, with the public receiving mixed messages. Furthermore, as flash flooding in particular is often localised and geographically variable providing locally specific messages would be difficult. Getting people to comprehend what the policy would mean for them and preparing themselves and their properties or place of work is a significant challenge.

4. Literature Review

Records for past floods show that exposure of the community to flooding can result in significant death tolls. Flood fatalities are significantly higher in flash flood events with rapidly rising violent flood flows than in comparably slower rising and moving riverine flooding. Two hundred and six (206) flash flood fatalities occurred in Australia between 1950 and March 2008 (Coates and Haynes, 2008). The cause of death for the majority of these cases was drowning. Other fatalities were a result of heart attacks or overexertion, or indirect causes such as electrocution or fallen trees (Coates and Haynes, 2008). Similarities have been observed in the United States, where 93 % of flash flood deaths can be attributed to drowning (French *et al.*, 1983). Details about the activity of flash flood victims immediately prior to death are available for just under 50 % of the victims. Of these, almost 53 % perished attempting to cross a watercourse, either by wading/swimming, or by using a bridge or ford (Coates and Haynes, 2008). These values include those in vehicles. The motivation behind the activity leading to the death was known for 47 % of the study group. Of these, almost 22 % were undertaking business as usual, either attempting to reach a destination, ignoring the flood warnings or unaware of the flood intensity (Coates and Haynes, 2008).

The majority (31 %) of the Australian flash flood fatalities, for which the mode of transport is known, were inside a vehicle at the time of death. Similar results have been observed around the world, 42 % of the 93 % US flash flood drowning fatalities were vehicle-related (French *et al.*, 1983) and 63 % of US riverine and flash flood fatalities were found to be vehicle-related (Ashley and Ashley, 2008). Jonkman and Kelman (2005) noted that vehicle-related fatalities occurred most frequently (33 %) in European and US floods.

The Lockyer Valley floods of January 2011 dramatically showed that sheltering in a residential building was also not a safe option. Of the nineteen people whom perished in the Lockyer Valley floods, thirteen were sheltering in buildings that were either completely inundated or collapsed under the force of the flood flows (Rogencamp and Barton, 2012).

Regardless, the high numbers of people that die in vehicles or on foot highlights the considerable risk in fleeing flash flood events. In many cases, people become exposed to greater risk when attempting to flee a flood affected area (Ashley and Ashley, 2008; Coates, 1999; Drobot and Parker, 2007; Jonkman and Kelman, 2005). The risks to those fleeing are not just the floodwaters themselves, but also include poor driving conditions, the danger of being hit by falling debris, electrocution from fallen power lines, lightning and mudslides (Haynes *et al.*, 2008).

Whilst evacuation is generally considered the safest of emergency management options during flood events, it is not always possible. Subsequently, it is an important aspect of emergency planning to ensure that in flood prone locations where timely evacuation may not be possible people will not be in greater danger remaining in their homes.

Jonkman and Kelman (2005) highlighted that in most floods, people are more likely to be killed or injured if they are outside of their home or in their cars during the flood. Subsequently, undertaking evacuation at inappropriate times, such as when the floodwaters have risen in depth and velocity, is likely to increase chance of death (Cave *et al.*, 2009).

In summary, people tend to be at risk in one of three main categories; on foot, in vehicles or in buildings. Subsequently, analysis of the literature has been divided into these three categories; people stability, vehicle stability and structural stability.

4.1 People stability

SCARM Report 73 Appendix J - Flood Hazard in *Floodplain management in Australia: best practice principles and guidelines* (SCARM, 2000), provides a brief discussion of pedestrian stability for consideration in estimating flood hazard. The two key mechanisms; loss of friction (sliding), and toppling (pushed over) by flowing water are highlighted as the basis of a presented figure considering the estimation of hazard along evacuation routes, relative to flow depth and velocity (Figure 2-2a).

Detailed review and consideration of appropriate safety criteria for people was undertaken as part of the current revision of Australian Rainfall and Runoff (ARR). The ARR report "Australian Rainfall and Runoff Revision Project 10: Appropriate Safety Criteria for People" (Cox *et al.*, 2010) includes a summary of relevant research and existing guidelines for safety of people in floodwaters in Australia.

Cox *et al.* (2010), like (SCARM, 2000), highlight that human stability within floodwaters has been found to be dependent on many factors. The two most important factors being flow depth and velocity, with depth found to dictate whether loss of stability is by sliding (friction) or tumbling (moment) failure.

Buoyancy increases at higher flows and reduces friction underfoot typically resulting in tumbling failure, while low depth-high velocity flows may cause sliding instability (Cox *et al.*, 2010). Cox *et al.*, (2010) suggests that higher depth, low velocity flows are the more dangerous case, as once footing is lost; a person is more likely to find it difficult to regain footing and drown. Losing footing in lower depths at higher velocity is considered less likely to result in a drowning fatality.

Cox *et al.* (2010) provides a summary of experimental data reported in international literature, and develops two sets of safety criteria based on re-analysis of data collated for previous laboratory and field investigations.

"For children with a height and mass product (H.M) of between 25 and 50 mKg, low hazard exists for flow values of D.V < 0.4 m^2/s, with a maximum flow depth of 0.5 m regardless of velocity and a maximum velocity of 3.0 m/s at shallow depths (D < 0.2 m). Under these flow regimes, the children tested retained their footing and felt "safe" in the flow. For adults (H.M > 50 mKg), low hazard exists for flow values of D.V < 0.6 m^2/s with a maximum depth limit of 1.2 m and a maximum velocity of 3.0 m/s at shallow depth (D < 0.3 m). Moderate hazard exists between D.V = 0.6 and 0.8 m^2/s, with a tolerable working flow regime of D.V < 0.8 m^2/s recommended for trained safety workers or experienced and well equipped persons. Significant hazard exists between D.V = 0.8 to 1.2 m^2/s, with the upper limit of stability observed during the majority of investigations of D.V = 1.2 m^2/s. Above this flow rate hazard is extreme and should not be considered safe for standing or traversing" (Cox *et al.*, 2010, p.18).

Table 4-1 provides a summary of proposed flow hazard regimes for children and adults, while Figure 4-1 graphically presents this information.

Table 4-1: Flow hazard regimes for infants, children and adults (After Cox *et al.*, 2010)

<table>
<tr><th>D x V (m^2s^{-1})[1]</th><th>Children[2]
(H.M = 25 to 50)</th><th>Adults
(H.M > 50)</th></tr>
<tr><td>0</td><td>Safe</td><td>Safe</td></tr>
<tr><td>0 – 0.4</td><td>Low Hazard[1]</td><td rowspan="2">Low Hazard[1]</td></tr>
<tr><td>0.4 – 0.6</td><td>Significant Hazard; Dangerous to most</td></tr>
<tr><td>0.6 – 0.8</td><td rowspan="3">Extreme Hazard; Dangerous to all</td><td>Moderate Hazard; Dangerous to some[3]</td></tr>
<tr><td>0.8 – 1.2</td><td>Significant Hazard; Dangerous to most[4]</td></tr>
<tr><td>> 1.2</td><td>Extreme Hazard; Dangerous to all</td></tr>
</table>

Notes:

1. **Maximum depth stability limit of 1.2m for adults and 0.5m for children** under good conditions. **Maximum velocity stability limit of 3.0 ms^{-1}** for both adults and children.
2. More vulnerable community members such as infants and the elderly should avoid exposure to floodwater. Flood flows are considered extremely hazardous to these community members under all conditions.
3. Working limit for trained safety workers or experienced and well equipped persons (D x V < 0.8 m^2s^{-1})
4. Upper limit of stability observed during most investigations (D x V > 1.2 m^2s^{-1})

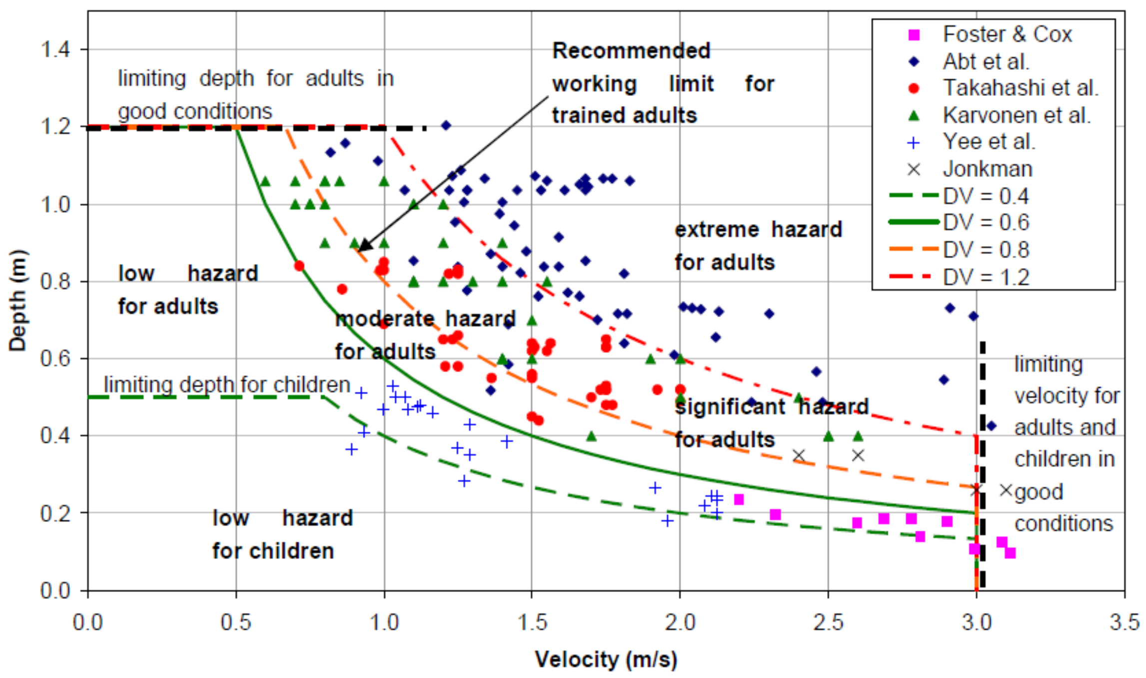


Figure 4-1: Proposed hazard regimes as a function of depth and velocity and compared to available experimental data (Source: Cox *et al.*, 2010)

Not included in the work presented by Cox *et al.*, is experimental testing conducted in Spain, presented by Gomez *et al.* (2010) and Russo *et al.* (2011). Eight hundred and thirty-four (834) tests, with (23) human subjects, were carried out in a Spanish flume facility. The testing methods of Gomez *et al.* (2010) and Russo *et al.* (2011) differed somewhat from other experiments. This experiment focussed on pedestrian safety in flooded roadways. The experimental method required that each test subject stepped off a road kerb into a shallow, relatively fast moving flow and then walked across the direction of flow as if crossing the roadway. This differed significantly from the other test data sets where subjects moved and turned predominantly in the main direction of the flow. Experimental results also showed that pedestrians were most unstable when first stepping from the kerb into the flow when all load bearing in the flow was on one foot (Gomez *et al.*, 2010; Russo *et al.*, 2011). In many respects instability thresholds recorded by this experimental method, while arguably recording a valid case, are more conservative that the other experimental data sets. These tests also consider the case of shallow depth at high velocity that is considered less likely to result in a fatality than the case of a person losing footing in a deeper flow

The aforementioned recommendations by Cox *et al.* (2010) have been incorporated in the ARR revisions, with the draft Chapter 6 of Book 9 "Safety Design Criteria" (Smith and Cox, 2013) released in December 2013.

4.2 Vehicle stability

As outlined by HR Wallingford *et al.* (2006), there are essentially three reasons why vehicles cannot be used in floodwaters:

- The presence of water stops the engine functioning;
- The vehicle floats; and
- The vehicle becomes difficult to control.

The safety of people during flood events can be compromised when vehicles they are travelling in are exposed to flood flows which cause the vehicle to become unstable by losing traction (frictional instability) or become buoyant (floating), leading to the vehicle being swept downstream (SCARM, 2000; Shand *et al.*, 2011). Limited definitive information exists regarding vehicle stability in floodwaters; however, leading guidelines and research are summarised in this section.

SCARM Report 73 Appendix J (SCARM, 2000) mentions that there are a broad range of stability estimation procedures available for estimating flood hazard in cars, however these procedures are considered to be inconsistent, inadequate and outdated (SCARM, 2000). Subsequently, no recommendations are provided for relationships between depth and velocity when considering vehicles stability in the SCARM report.

Safety criteria for vehicles have recently been reviewed as part of the ARR revision process. The report "Australian Rainfall and Runoff Revision Project 10: Appropriate Safety Criteria for Vehicles" (Shand *et al.*, 2011), includes a summary of relevant research and existing guidelines for safety of vehicles on floodways in Australia. Shand *et al.* (2011) highlights that guidelines provided for vehicle stability on floodways have generally been based on the product of depth and velocity, as derived during scaled experimental investigations of stationary vehicle stability in the late 1960s and early 1970s, and theoretical analysis conducted in the early 1990s.

Shand *et al.* (2011) summarise these studies, highlighting that due to substantial changes in vehicle design since the original studies, the criteria in Australian Rainfall and Runoff (I.E.Aust, 1987) require revision. Based on available experimental and analytical data, draft criteria for stationary vehicle stability (Table 4-2) are proposed for three vehicle classes (small passenger, large passenger and 4WD). Importantly, the criteria proposed by Shand *et al.* (2011) have taken into consideration the safety criteria for people (Cox *et al.*, 2010), ensuring that, in event of vehicle failure, safety was not compromised once people abandoned their cars.

Shand *et al.* (2011) highlighted that the available scaled experimental data is being applied beyond its limits to develop these draft criteria, and that the criteria are unlikely reliable enough to be adopted permanently as safety criteria. This is due to the data not allowing adequate assessment of:

- Appropriate coefficients of friction for use in flood flows;
- Buoyancy in modern cars;
- The effect of vehicle orientation to flow direction (including vehicle movement); and
- Information for additional categories including small and large commercial vehicles and emergency service vehicles.

Table 4-2: Proposed draft interim criteria for stationary vehicle stability (After Shand *et al.*, 2011)

Class of Vehicle	Length (m)	Kerb Weight (kg)	Ground clearance (m)	Limiting still water depth[1]	Limiting high velocity flow depth[2]	Limiting velocity[3]	Equation of stability
Small passenger	< 4.3	< 1250	< 0.12	0.3	0.1	3.0	D.V ≤ 0.3
Large passenger	> 4.3	> 1250	> 0.12	0.4	0.15	3.0	D.V ≤ 0.45
Large 4WD	> 4.5	> 2000	> 0.22	0.5	0.2	3.0	D.V ≤ 0.6

[1] At velocity = 0 m/s; [2] At velocity = 3 m/s; [3] At low depth

Both SCARM (2000) and Shand *et al.* (2011) recommend a comprehensive testing program prior to development of definitive design guidelines for vehicle stability.

Some recent investigations of vehicle stability, are not included in the review by Shand *et al.* (2011). Experimental investigations have been undertaken using model die-cast vehicles in a horizontal hydraulic flume at the Hydro-environmental Research Centre of Cardiff University, United Kingdom (Shu *et al.*, 2011; Xia *et al.*, 2011). These studies evaluated the theoretical forces exerted on a fully submerged and static vehicle under flow conditions to derive an expression for the instability threshold. The drag and frictional coefficients are included implicitly within the expression and derived by laboratory flume testing using model vehicles. This methodology differs from previous studies, where reaction forces were measured for a geometrically scaled vehicle subject to flows and instability threshold calculated for various coefficients of friction.

Xia *et al.* (2011) tested three types of vehicle using an initial geometric scale of 1:43 with verification tests at a larger 1:18 scale. Shu *et al.* (2011) tested the same three vehicle types undertaking all tests at 1:18 scale. Both testing programs assumed all wheels to be locked and the vehicle orientated parallel to the flow direction. Velocity is increased for a given depth until vehicle motion is initiated. Experimental results are used to calibrate the parameters within the theoretical expression for instability thresholds.

The studies differ in that Xia *et al.* (2011) ddid not correctly scale the density and therefore mass of the model vehicles according to dynamic similarity principles but rather used a relative density term. The resultant values differ significantly from other studies (by up to order of magnitude) with vehicles becoming submerged before moving and are inconsistent with qualitative evidence from the field (i.e. during the Queensland floods in February 2011 and the Japan Tsunami in March 2011) where cars float well before the vehicles become submerged. The values found by Xia *et al.* (2011) are therefore not considered further in the present reanalysis.

Shu *et al.* (2011) correctly scaled the density and mass of model vehicles and obtained D.V values slightly higher than those found in earlier investigations. Shu *et al.* (2011) had the model test vehicles filled with foam to resist ingress of water. This was thought to better represent modern vehicles with significantly improved dust seals than the older cars tested in most other investigations. Shu *et al.* (2011) determined the friction coefficients to range from 0.39 to 0.68 for their models, quoted to be within prototype ranges given by Gerard (2006). The differences in stability thresholds is likely due to the higher coefficient of friction in the Shu *et al.* (2011) models ($\mu = 0.39$ to 0.68) compared to the lower values adopted by earlier studies (e.g. Bonham and Hattersley, 1967; Keller and Mitsch, 1993) ($\mu = 0.3$). Sensitivity testing using a reducing frictional coefficient ($\mu = 0.5$) gives lower critical D.V values and may tend toward those found in earlier studies. The authors acknowledge that in prototype vehicles, mass is not evenly distributed leading to the rear of a vehicle often floating first. This prevents the rear wheels from contributing friction to prevent motion. The model vehicles have more evenly distributed mass and therefore do not accurately represent this occurrence and may therefore be non-conservative.

Shu *et al.* (2011) verified their results against two field observations of cars moving during flood events. However, the limited number of verification cases and the fact that the cars were already moving at the time of observation yields the robustness of such verification questionable. The threshold of vehicle motion and the flow rate, which may be considered safe for vehicle passage are likely to be lower than values observed for vehicles already moving in flood flow

It should be noted, that like SCARM (2000) and Shand *et al.* (2011), both Xia *et al.* (2011) and Shu *et al.* (2011) recommended full scale testing to investigate thresholds of flooded vehicles under real and more complex circumstances.

The aforementioned recommendations by Shand *et al.* (2011) have been incorporated in the ARR revisions, with the draft Chapter 6 of Book 9 "Safety Design Criteria" (Smith and Cox, 2013) released in December 2013.

4.3 Structural stability

While there is minimal information in *Floodplain management in Australia: best practice principles and guidelines* (SCARM, 2000) about building stability, existing flood hazard curves (e.g. BMT WBM, 2012) often refer to a building stability threshold. Indeed, in some urban jurisdictions where flash flooding is prevalent, recent floodplain management plans are recommending that residents shelter in place during extreme flood events (BMT WBM, 2012;

TSC, 2012). If building stability thresholds are used to define conditions to identify safe shelters in urban environments, it is important to understand the basis of flood hazard curves for building stability, as well as the different mechanisms by which structures may fail under flood conditions.

Unlike considerations for people and vehicle stability, the recent ARR revision projects do not consider structural stability during flood events. This report section outlines both guidelines and research that consider structural stability during flood events and presents a range of hazard curves for structural stability.

4.3.1 Forces of concern and failure mechanisms

The Australian Building Codes Board (ABCB, 2013) identify a range of forces that might affect building stability including:

- Hydrostatic actions;
- Hydrodynamic actions;
- Debris actions;
- Wave actions from wind and wakes; and
- Erosion and scour due to flood actions.

While the *Construction of Buildings in Flood Hazard Areas* code (ABCB, 2013) identifies that the aforementioned forces occur during flood events, it does not provide direct guidance on how these forces should be estimated or combined when considering building design in flood areas. Further to this information, Kelman and Spence (2004) provide an overview of flood characteristics with respect to their applicability for estimating and analysing direct flood damage to buildings.

HR Wallingford *et al.* (2003, p.66) highlight some very important points for consideration of building failure in flood events:

> *At velocities in excess of 2 m/s, the stability of foundations and poles can be affected by scour. As grass and earth surfaces begin to erode, scour holes can develop. At depths in excess of 2 m, lightly framed buildings can be damaged by water pressure, floatation and debris impact, even at low velocities. Where buildings are "flood proofed", and there is a higher level of water outside than inside, the maximum differential pressure that brickwork walls can resist is of the order of one metre.*

RESCDAM (2001) also states that velocities of greater than 2 m/s will likely result in either partial or total damage for masonry, concrete and brick buildings.

For catastrophic flooding, (Becker *et al.*, 2011) considers three major failure mechanisms that can occur making the building unsafe:

- The building can fill with water to a depth that is unsafe for people inside (fill);
- Floodwaters may cause structural damage that could lead to building collapse and injury to occupants, or even death (collapse); and
- The buoyant and lateral force of the water may overcome the strength of the anchors and weight of the building holding it to its foundation (float).

The recent Australian flooding disaster of January 2011 in the Lockyer Valley, highlights the importance of a safe flood refuge. During this flash flood event a staggering thirteen (13) of the nineteen (19) people killed during the flood were washed out of their houses, disappeared as the house was washed away or drowned in their house (Rogencamp and Barton, 2012). Further, a total of 120 houses were structurally damaged by the flood. Many of these were either totally destroyed during the flood event or were deemed to be structurally unsound because of the flood and subsequently demolished. Modelling suggests that D x V products of more than 3 m^2/s were experienced in much of the Grantham town area with some areas above 5 m^2/s. Figure 4-2 presents the peak modelled D x V at Grantham on the 10th of January 2011.

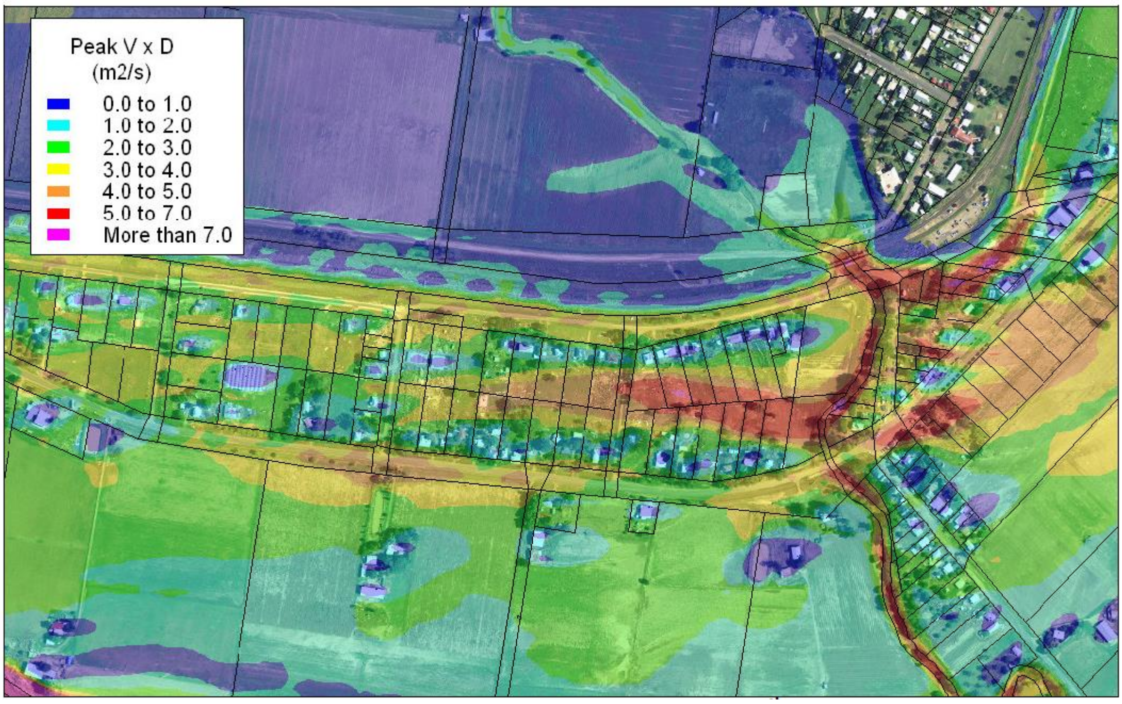


Figure 4-2: Peak modelled D x V at Grantham, 10th January 2011 (Source: Rogencamp and Barton, 2012)

4.3.2 Structural stability in tsunamis

While perhaps not directly applicable to catchment floodplain management, a great deal of research has been undertaken to understand the forces and impacts on structures during tsunamis, essentially an extreme flooding event. The forces and impacts on structures discussed are not dissimilar to those mentioned by the ABCB (2013), with literature (e.g. Al-Faesly *et al.*, 2012; FEMA, 2012; Pacheco and Robertson, 2005) citing the following:

- Hydrostatic forces resulting from standing water or slow moving flow around the structure;
- Buoyant forces due to displaced volume of water;
- Hydrodynamic forces arising from moderate-to-high-velocity water flow around the structure;
- Impulsive forces caused by the leading edge of the water impacting the structure;
- Debris impact forces generated by floating debris colliding with the structure;
- Breaking wave load conditions;
- Localised scours;

- Uplift forces on elevated floors of a structure that are submerged during tsunami inundation; and
- Damming of waterborne debris due to the accumulation of debris on the upstream side of the structure, which results in an increase in the hydrodynamic force.

Subsequently, studies considering structural stability in tsunamis have also been considered in the following discussion. FEMA (2012) provides a detailed discussion of all relevant force calculations.

Studies of damage from historic tsunamis have shown that building survivability varies with construction type and tsunami run-up height (FEMA, 2012). Data from the 1993 Okushiri Tsunami, and earlier tsunamis, was analysed, with results suggesting that for a given tsunami height, wood frame construction experienced considerably more damage and was frequently destroyed, while reinforced concrete structures generally sustained only minor structural damage. More recent data, including that resulting from the 2004 Indian Ocean Tsunami, supports this conclusion (FEMA, 2012).

Extensive building damage due to waterborne debris and scour of structural elements is often observed following tsunamis, including damage to structural elements of non-engineered reinforced concrete buildings, and debris damming resulting in damage to structural members (FEMA, 2012). Whilst the conditions leading to these impacts may be considered extreme compared to catchment flooding, they highlight the substantial damage that can occur from waterborne debris, as well as scour. From a review of available data taken by various survey teams following tsunamis, scour depths as large as 3 m have been observed on shore (this in Khao Lak, Thailand) (FEMA, 2012).

Under a 2005 Japanese Cabinet Office guideline, buildings designated as tsunami shelters should be made of concrete or other similarly robust materials. They should be at least three stories high in areas where flood levels are predicted to reach two meters, or at least four stories high if flood levels are predicted to reach three meters (FEMA, 2012). During the 2011 Japanese tsunami, many of the designated vertical evacuation buildings were not tall enough for the flow depths encountered, and many people who sought refuge in these structures did not survive the inundation, despite the structures remaining intact. While the flood hazards described here are extreme, the guidance does highlight the requirements needed to ensure safety in extreme events. Section 3.3.3 highlights that effective flood shelters need to consider floods more extreme than the defined flood event up to the PMF or a similar extreme flood event.

In addition to this, during the 2011 Japanese tsunami, some concrete and steel buildings were sufficiently open to relieve hydrostatic uplift but were still toppled by hydrodynamic forces of the incoming or returning flow (FEMA, 2012). Figure 4-3 shows a three-story reinforced concrete building frame with shear walls on a 0.9 meter-thick mat foundation, which overturned toward Onagawa Bay during the tsunami return flow.

Figure 4-3: Overturned three-storey commercial building on mat foundation (Source: FEMA, 2012)

Uplift forces have been observed in both tsunamis and other extreme flooding events, such as Hurricane Katrina (see Figure 4-4). Uplift loading applied to the underside of floor systems has been blamed for the collapse of elevated floor levels in numerous engineered structures (FEMA, 2012). As an example, car parks in New Orleans were susceptible to upward loading caused by additional buoyancy forces from air trapped below, and upward hydrodynamic forces applied by the surge and wave action (FEMA, 2012). While most failures of this type did not result in collapse of the entire structure, loss of floor framing can lead to column damage, increased unbraced lengths, and progressive collapse of a disproportionate section of the building (FEMA, 2012).

Figure 4-4: Structural damage due to uplift forces – Hurricane Katrina 2005 (Source: FEMA, 2012)

4.3.3 Hazard curves

Numerous hazard threshold curves collated from international literature are collated and compared in Figure 4-5. The collated curves have a variety of origins. As discussed by Leigh (2008), it can be difficult to synthesise the different building stability curves and associated data, as they are derived by various means of analysis. Subsequently, comparison between theory based curves, (e.g. Black, 1975; Dale *et al.*, 2004), field derived curves (e.g. Clausen and Clarke, 1990) and curves derived from modelling and analysis (e.g. Becker *et al.*, 2011) is difficult. Further, different damage thresholds may apply for each of these curves. The spread of curves in Figure 4-5 highlights the overall uncertainty surrounding building stability during flood events.

Investigation and review of the available information concerning the failure of building structures under flood loads has also been conducted by Kelman and Spence (2004) and Leigh (2008). Amongst a range of relevant conclusions, these reviews noted that while a series of studies had theoretically analysed incident flood forces compared to the resisting strength of various building structures, most of these studies had considered components of flood forces in isolation or in limited combinations e.g. hydrostatic and simplified hydrodynamic (velocity head) or buoyancy and drag forces.

The following summary provides information about the sources of each of these curves, and their applicability for considering building stability during flood events in the Australian environment.

The earliest of these building stability studies, the 'Black Curves', are an often cited reference for flood risk management and flood damages undertaken for the US Department of Commerce (Black, 1975). The curves were developed for buildings in rural floodplains in the USA where the assumption of single depth, averaged velocity for the incident flows impacting the buildings was considered reasonable. The methodology used to develop the combinations of depth and velocity to cause building failure was theoretically determined. The basis of the methodology was to determine the buoyant force acting on a typical building at a range of flood depths. Once the buoyant force had been determined at each adopted depth, the theoretical horizontal force due to water flowing past the building was calculated. If the calculated theoretical flow drag force was equal to or greater than the friction force to keep the house on its foundations, then the house was considered to have failed structurally. The drag force was then used to calculate a depth averaged incident flow velocity based on an assumed drag coefficient. The analysis assumed that the flood levels had equalised inside and outside of the structure in this analysis.

The investigations of Black (1975) were adapted by Dale *et al.* (2004) to Australian building types. This adaptation included calculations for houses with an L-shape and area of 192.7m^2. This was considered to better represent the typical wood framed house in Australia. Comparison of the curves developed by Black (1975) and Dale *et al.* (2004) shows that the update to Australian conditions produced curves indicating Australian houses to be more resilient to flood flows than the structures investigated in the original USA analysis. Four curves were presented by Dale *et al.* (2004), all representing timber framed structures with combinations of wall (fibro or brick) and roof (tile or steel) construction types.

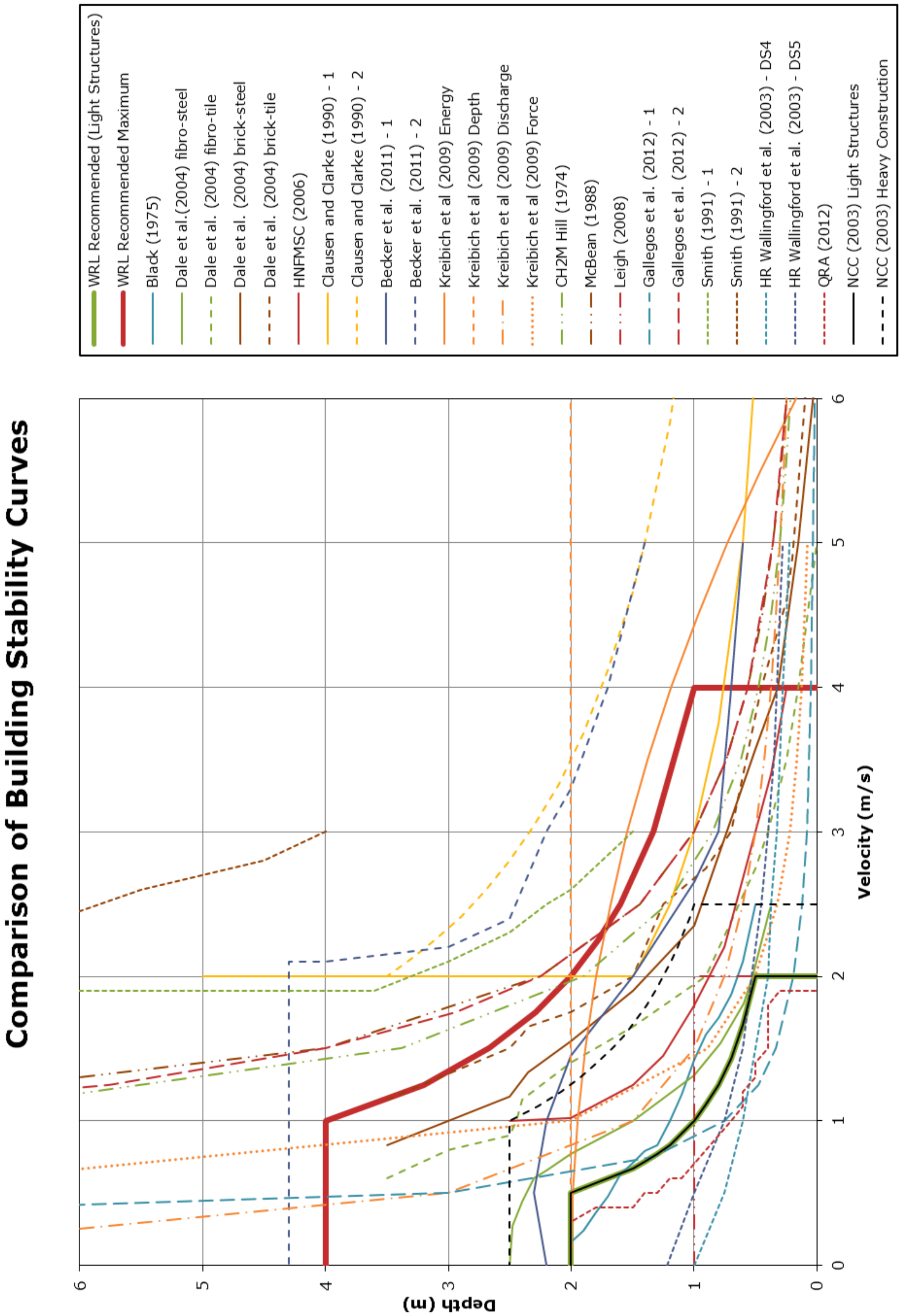


Figure 4-5: Comparison of building stability curves

Floodplain management studies in the Hawkesbury-Nepean River floodplain conducted in the 1990's stimulated consideration of the resilience of residential houses to floods in this area. An analysis of the flood forces required to initiate structural failure of residential buildings typical of the Hawkesbury-Nepean floodplain was conducted by Page (2000). This analysis considered the resistance of the structural integrity of various building construction types to flood flows and considered several failure cases including the case of unequal floodwater depths (unequal hydrostatic forces) inside and outside of a flooded building. Again, this analysis used theoretical methods to calculate the average flood force per unit width required to cause building wall failure. The analysis combined the hydrostatic force of the floodwater depth with an additional hydrodynamic force component derived as an equivalent 'velocity head' to provide combinations of flood flow depth and velocity for building wall failure. The lower envelope of findings by Page (2000) appears to have been adopted as the basis of building stability curve offered in HNFMSC (2006c).

Hazard threshold curves presented in Figure 4-5 also include those developed by Clausen and Clarke (1990), and used for the basis of the guidance presented in the RESCDAM (2001) review for the European Union. These curves were developed using field data from the English Dale Dyke Dam failure in 1864, combined with numerical modelling of the flood wave to calculate depths and velocities. These values were then validated against the engineering report, detailing the dam breach and subsequent flood (Clausen and Clarke, 1990). Three levels of damage to impacted masonry structures were detailed: inundation damage, partial (or minor) damage and total destruction (or major damage). Both the partial damage (1) and total destruction (2) curves are presented in Figure 4-5.

Also presented in the RESCDAM (2001) review are critical water velocities and depths for masonry and concrete buildings, as presented by Smith (1991) and recreated in Figure 4-5. The original article could not be sourced for this report. Subsequently, little is known about the origin of these curves, other than they are for one (1) and two (2) storey masonry and concrete buildings.

Becker *et al.* (2011) investigated flood impacts on typical wood-frame residential homes in Canada using a theoretical method. The model was run for an array of 2,500 flood conditions combinations, using flood depths between 0 m and 5 m, and velocities reaching 5 m/s. Series of curves were developed using the results, with two of these (best and worst case scenarios for structural failure, discounting buoyant failure) included in Figure 4-5. It is important to note there may be substantial structural differences between typical wood-framed homes in Canada and Australia.

Four structural failure options investigated by Kreibich *et al.* (2009) are also included in Figure 4-5. This study considered the influences of flow velocity, water depth and combinations of these parameters for five communities affected by the Elbe catchment flood in Germany (2002). Numerical models were developed to calculate the depths and velocities at locations where damage occurred. Kreibich *et al.* (2009) determined that the energy head and depth criteria provided the best correlation between predicted and reported damage, followed by the flow force and flood intensity (D x V). There was no correlation between velocity alone and damage.

Gallegos *et al.* (2012) provide a comparison of several structural damage models, using the different methods to predict damage or destruction following the 1963 Baldwin Hills dam-break flood. One of the methods included is that presented by CH2M Hill (1974, in Gallegos *et al*. 2012). This force based relation is presented in Figure 4-5 and has been incorporated in the widely used *HAZUS-MH* software to predict the collapse of wood-framed homes (Gallegos *et al.*, 2012). Despite the authors' efforts, it was not possible to obtain the original report by CH2M Hill (1974) for this project.

Another hazard model is that presented by McBean *et al.* (1988a). Included in the review by Gallegos *et al.* (2012), McBean *et al.* (1988a, p. 640) state that "the force of water on a building is proportional to the square of velocity and the exposed area of the building face" and "a velocity of 3 m/s acting over a 1 m depth will produce a force sufficient to exceed the design capacity of a typical residential wall." Gallegos *et al.* (2012) interpreted this as $F = D \times V^2 > 9\ m^3/s^2$. This curve has been included in Figure 4-5. Houses studied for this project were primarily listed as masonry or wood frame (McBean *et al.*, 1988b).

HR Wallingford *et al.* (2003) present curves for damage to residential properties in eastern England based on the work of Kelman (2002). The lower bounds of two categories are reproduced in Figure 4-5:

a) DS4 – Structural damage to walls lead to water/debris entry; and
b) DS5 – Structural collapse and beyond repair.

Importantly, HR Wallingford *et al.* (2003) highlight that, in broad terms, buildings are more resilient to floodwaters than people, and further, that hazard functions derived for people do not apply to buildings.

The Newcastle City-wide Floodplain Risk Management Study and Plan (BMT WBM, 2012) includes a series of hazard curves (hydraulic behaviour thresholds), for the Newcastle LGA. These curves are derived from the Newcastle Flood Policy (NCC, 2003) and range from H1 (hydraulically stable for parked or moving cars) to H5 (generally unstable for any construction type). The H3 (hydraulically suitable for light construction (e.g. timber frame and brick veneer), but not for vehicles or for wading) and H4 (hydraulically suitable for heavy construction (e.g. steel frame and reinforced concrete) only) curves are included in Figure 4-5. The method for derivation of these curves is not detailed in the Newcastle Flood Policy.

Gallegos *et al.* (2012) conducted a numerical investigation using ten structural damage model curves to predict damage to an area of houses following the 1963 Baldwin Hills dam-break flood. The event caused high-velocity flows exceeding 5 m/s, resulting in the structural failure of forty-one (41) wood-framed residences built in the 1940s. Of the forty-one (41), sixteen (16) were completely washed out. Amongst the hazard curves investigated there were varying results, with solely depth based curves producing the least accurate results, and flow force being a good predictor for both moderate and severe damage. The force thresholds developed through calibration for moderate (1) and severe (2) damage are presented in Figure 4-5.

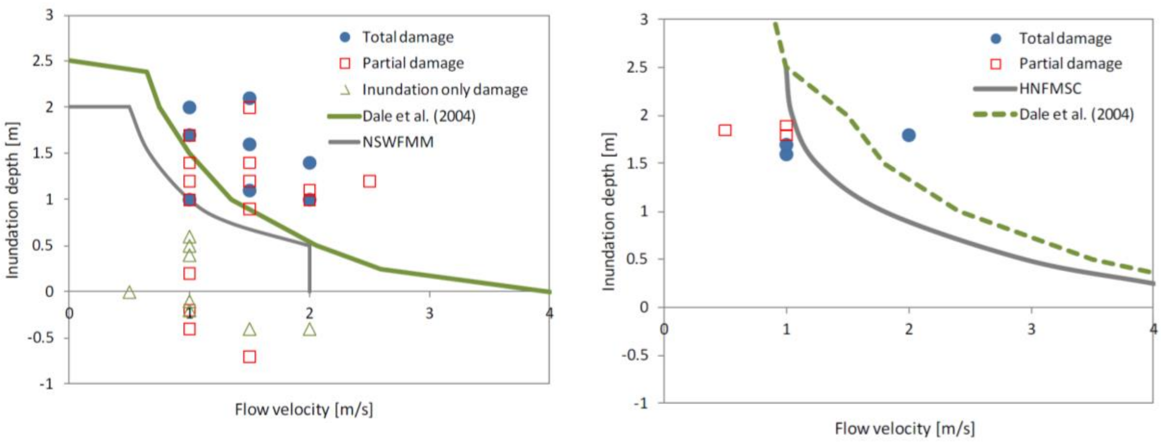
Leigh (2008), in a literature review regarding the suitability to 'shelter-in-place' during a flash flood event suggested conservatively that cavity brick and timber-framed brick veneer slab-on-ground dwellings common in NSW could be considered suitable for sheltering in place if the following flood characteristics are satisfied:

- $D \times V \leq 2.0\ m^2/s$, and
- $D \leq 1.0$ m, and
- $V \leq 2.0$ m/s.

This advice is also included in Figure 4-5.

Figure 4-5 also presents a curve outlined by the Queensland Reconstruction Authority (QRA, 2012). This curve presents "significant" hazard, as outlined in their figure, representing, among other things, the "Building Code limitation", thought to be interpreted from both the national and Queensland building codes (ABCB, 2013; BCQ, 2013) as the 'deemed-to-satisfy' standard.

Mason *et al.* (2012) presents an analysis of damage to buildings following the 2010-11 Eastern Australia floods. Utilising observations of damage to buildings in Brisbane, Ipswich and Grantham, a predictive model for estimating flood loss and occupant displacement was been developed. This model can be used for flood risk assessments or rapid assessment of impacts following a flood event (Mason *et al.*, 2012). The report provides an overview of flood actions on buildings and methods for protecting buildings from flood actions, however the analysis of damage data focuses on economic losses, in particular relative to depth. In Section 5.3.3 of Mason *et al.* (2012) there is a discussion of the influence of flood flow velocity on building damage, with damage extents for raised-floor timber-clad buildings and slab-on-ground brick buildings plotted against previously reported failure thresholds (Figure 4-6).



(a) **(b)**

Figure 4-6: Damage extents for raised-floor timber-clad buildings (a) and slab-on-ground brick buildings (b) assessed in Grantham compared with predicted failure thresholds (Source: Mason *et al.*, 2012)

The results presented in Figure 4-6 highlight that the curves recommended for use by this report's authors (presented in Figure 4-5) are representative of the damage conditions for depth and velocity combinations observed in local Australian flood events.

Also presented for comparison in Figure 4-5 are two curves recommended for use by this report's authors. Further explanation of these building stability threshold curves is provided in Section 5.3.

4.3.4 Guidance for construction in flood prone areas

As previously mentioned, the Australian Building Codes Board has released a standard, *Construction of Buildings in Flood Hazard Areas* (ABCB, 2013), detailing guidance for construction in flood hazard areas. This standard focuses on the design and construction of new buildings in flood hazard areas, rather than the hazard levels of pre-existing buildings and developments. No specific consideration is given to hazard curves for building stability under flood flow conditions. This standard has provided the basis for guidelines developed by Building

Codes Queensland (BCQ, 2012; 2013). Again, no hazard curves for building stability under flood flow conditions are included in these documents.

The Hawkesbury-Nepean Floodplain Management Steering Committee have released a series of documents considering guidance for land use planning, building and subdivision design for flood prone areas (HNFMSC, 2006a; b; c). These three documents provide a thorough overview of considerations for building construction in flood prone areas.

In the United States of America, Standard ASCE/SEI 24-05 *Flood Resistant Design and Construction* (ASCE, 2006) provides minimum requirements for flood-resistant design and construction of structures located in flood hazard areas. Revising the earlier ASCE/SEI 24-98 (ASCE, 2000), this standard applies to new structures, including subsequent work, and to substantial repair or improvement of existing structures that are not historic structures. Specific topics include: basic requirements for flood hazard areas; high-risk flood hazard areas; coastal high-risk hazard areas and Coastal A Zones; materials; dry and wet flood proofing; utilities; building access; and miscellaneous construction (ASCE, 2006). This reference also stipulates that design of structures within flood hazard areas be governed by the loading provisions of ASCE 7 Minimum Design Loads for Buildings and Other Structures. Specific guidance applies to structures built in areas of high velocity flow. High velocity flow is defined as *"during design flood or lesser conditions, water movement adjacent to structures and/or foundations with flow velocities greater than 10 ft./sec."* (3.05 m/s) (ASCE, 2006, p.4).

Standard ASCE/SEI 7-10 *Minimum Design Loads for Buildings and Other Structures* provides general requirements for structural design, including the calculation of forces arising from floods and waves on specific types of structural elements. The standard also covers definitions that relate to flood areas or coastal high-hazard areas associated with tides, storm surges, riverine flooding, seiches, and tsunamis (ASCE, 2013).

The Federal Emergency Management Agency Coastal Construction Manual (FEMA, 2011) has the objective to provide design and construction guidance for structures built in coastal areas throughout the United States in order to resist the effects of storm and hurricane surge and wave action. Expressions are provided for flood and wave loads on specific types of structural members, as well as a discussion of flood hazard and coastal building site selection. The code also recommends certain loading combinations for specific types of structural elements.

5. Updated Flood Hazard Thresholds (Vulnerability Curves)

Section 3 of this report provides a summary of the issues and considerations when quantifying flood hazard for floodplain management. A key part of the flood hazard assessment process is a set of sound and defensible criteria to relate the quantified physical flood behaviour in terms of flood depth and velocity to the vulnerability of the community exposed to flooding. Section 4 collates and summarises available information describing community vulnerability. Community vulnerability has been described by threshold criteria for the stability of people, vehicles and buildings when exposed to flood hazard.

Information collated from all available sources as summarised in Section 4 has been further interpreted and simplified in the following report sections into a series of hazard threshold curves, which the authors suggest can be used to classify flood hazard to support floodplain management decision makers.

5.1 People stability

Safety criteria for people stability have been comprehensively reviewed as part of the ARR revision process. The people stability criteria as recommended in *Australian Rainfall and Runoff Revision Project 10: Appropriate Safety Criteria for People*, (Cox *et al.* (2010)) are reproduced in Figure 5-1. These criteria are recommended for all flood hazard assessments where the stability of people in flood flows is relevant.

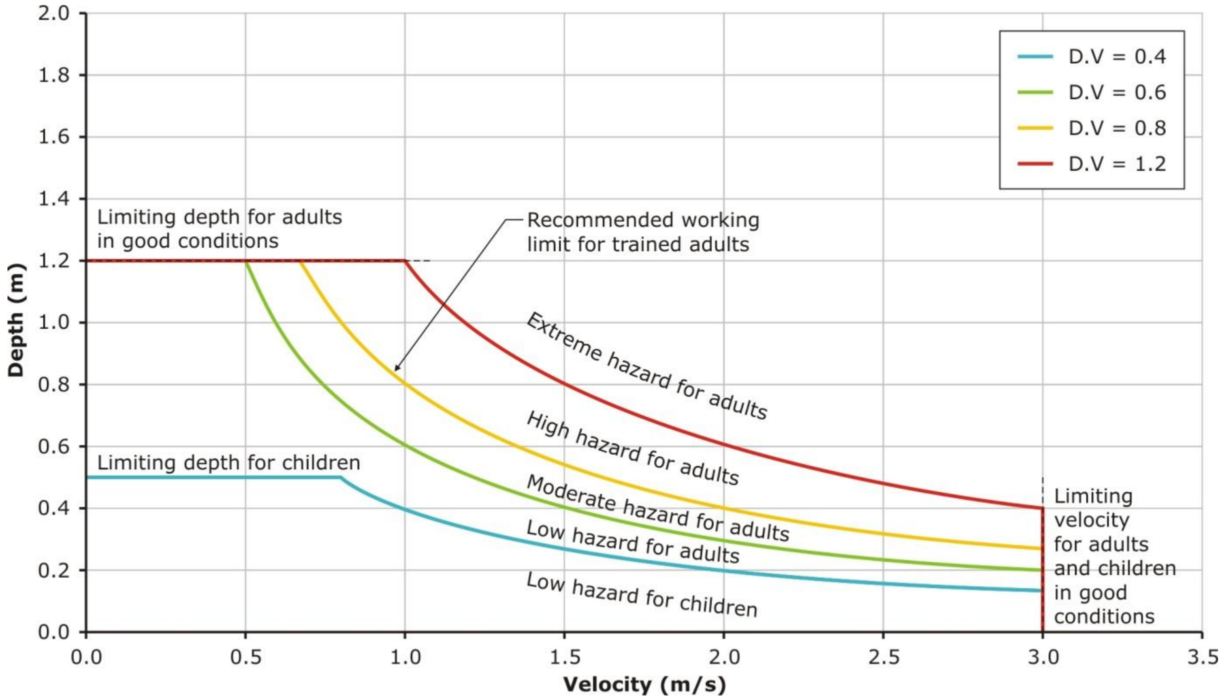


Figure 5-1: Thresholds for people stability in floods (After Cox *et al.*, 2010)

5.2 Vehicle stability

Similarly, safety criteria for vehicle stability have been comprehensively reviewed as part of the same ARR revision process. Draft safety criteria for vehicle stability proposed by Shand *et al.* (2011) are reproduced in Figure 5-2. These criteria are recommended for all flood hazard assessments where the stability of people in flood flows is relevant.

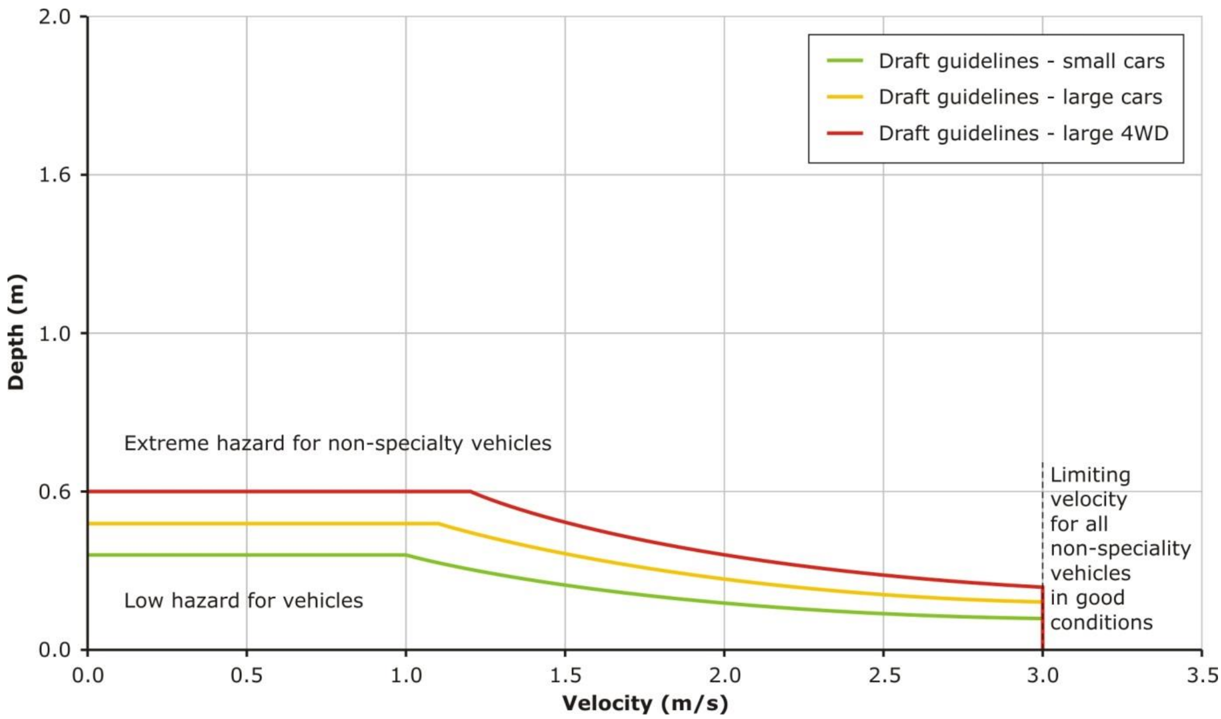


Figure 5-2: Thresholds for vehicles stability in floods (After: Shand *et al.*, 2011)

Note however, that as discussed in Section 4.2, Shand *et al.* (2011), while the best available, the experimental data for vehicle stability is being applied beyond its limits to develop these draft criteria, and that they are unlikely reliable enough to be adopted permanently as safety criteria. A comprehensive testing program is required prior to development of definitive design guidelines for vehicle stability.

5.3 Building stability

A thorough examination of building stability during flood has been completed as part of this project and is reported in Section 4.3. Proposed stability criteria for buildings are presented in Figure 5-3.

Section 4.3 discusses the considerable variability in the range of criteria specified in literature for the stability of buildings of varying construction types exposed to floodwaters. While the considerable variability in building construction is acknowledged, the analysis of building damage leading to collapse reported by Mason *et al.*, (2012) for the Lockyer Valley floods in January 2010 is compelling. This analysis shows that buildings constructed for Australian conditions are vulnerable to damage and collapse under flood hazard conditions at the lower end of the scale presented in Figure 4-5.

On this basis, the green curve in Figure 5-3 is proposed as a lower threshold for residential homes, built without consideration of flood forces. This curve can be used as a minimum criteria for building stability in existing flood affected areas.

The hazard zone between the green curve and the upper limit red curve in Figure 5-3 identifies flood hazard conditions where it is considered, if required, possible to construct a purpose built structure that is an appropriately engineered structure specifically designed to withstand the full range of anticipated flood forces including:

- **Hydrostatic forces** resulting from standing water or slow moving flow around the structure;
- **Buoyant forces** due to displaced volume of water;
- **Hydrodynamic forces** arising from moderate-to-high-velocity water flow around the structure;
- **Impulsive Forces** caused by the leading edge of the water impacting the structure;
- **Uplift forces** on elevated floors of a structure that are submerged during a flood event;
- **Debris Impact Forces** generated by floating debris colliding with the structure;
- **Damming of Waterborne Debris** due to the accumulation of debris on the upstream side of the structure, which results in an increase in the hydrodynamic force.
- **Wave actions** from wind and wakes; and
- **Erosion and Scour** due to flood actions.

In locations where timely evacuation is not possible, such purpose built structures may be required for vertical evacuation, not dissimilar to the process used in Japan for tsunamis. However, it would be important to ensure the structure was purpose built for the conditions it would be likely to encounter, up to and including the PMF or a similar extreme flood event. The bottom floor of such structures may need to be somewhat sacrificial during a flood event, for example, the windows and doors may 'blow out' under high flow conditions, however the building's structural members will be required to remain intact.

Dalrymple and Kriebel (2005) suggested that the nature of buildings played a key part in the reduction of structural damage to many hotel buildings in Thailand during the 2004 Indian Ocean Tsunami. Reinforced concrete buildings with sliding glass doors facing the sea and the backs of the buildings *"suffered little structural damage as the force of the tsunami broke through all of the doors and windows, thus reducing the force of the water on the building itself. By contrast, concrete buildings with solid masonry in-fill walls and no flow-through capability often experienced destruction of the walls and, in many cases, damage to the load-bearing structural frame."* (Dalrymple and Kriebel, 2005, p.7).

The red curve in Figure 5-3 is a suggested upper limit for all buildings. Buildings in areas classified with flood hazard above this threshold are considered vulnerable to collapse under these extreme flood conditions.

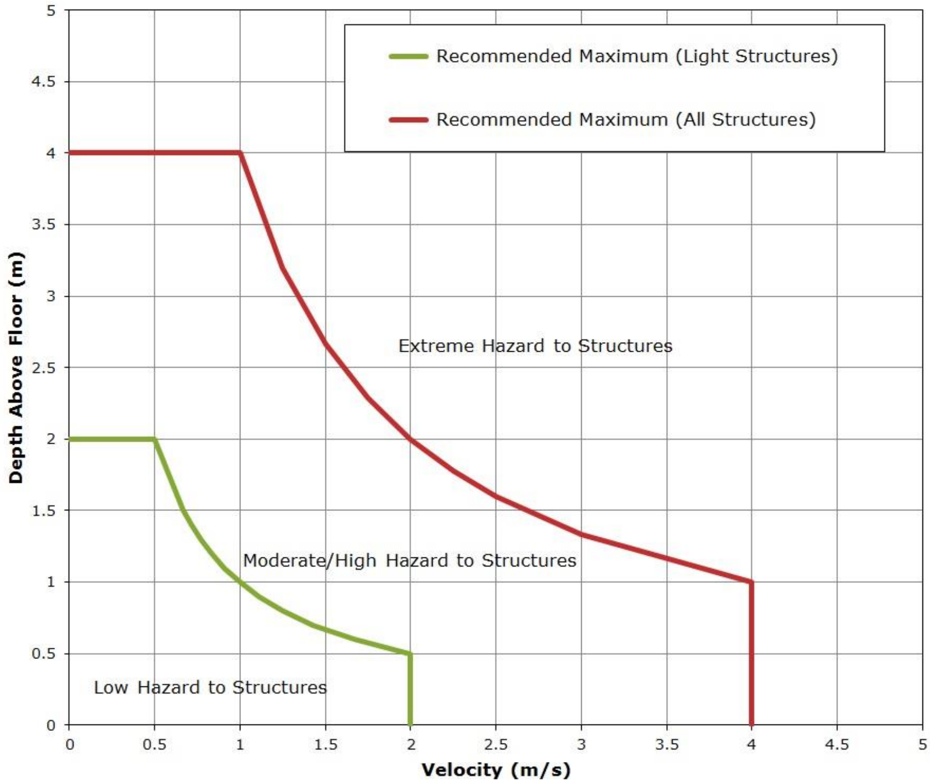


Figure 5-3: Proposed thresholds for building stability in floods

5.4 Comparison of hazard curves for people, vehicle and building stability

Previous hazard classification curves (e.g. SCARM, 2000, HNFMSC 2006a, NCC 2003) provided a single set of hazard curves that divided flood hazard levels into generic classifications of low, medium, high etc. While the thresholds between these classifications had some basis in data collected for stability/vulnerability of people and risk to life, in practice, such threshold curves have been widely interpreted (sometimes mis-interpreted) and applied in myriad ways.

It is interesting to compare the curves summarised for people, vehicle and building stability compiled for this report. Figure 5-4 provides a direct comparison of these three sets of curves. The first observation to be made is that for slow moving floodwaters at depths greater than 0.5m, adults wading through floodwater are generally considered more stable than vehicles i.e. in most cases, vehicles are equally unstable or more unstable than adults wading through the same flow conditions. Secondly, the stability limit for an untrained adult walking through floodwater (D x V = 0.8) is almost the same level as the lower threshold limit for building stability (D x V = 1.0). Also, that for shallow fast moving flows, building stability (through foundation erosion/scour) may be less than the stability of a person walking through the same flow conditions. In some situations, this means that you would be safer to walk out through the prevailing floodwaters rather than sheltering in a poorly constructed building.

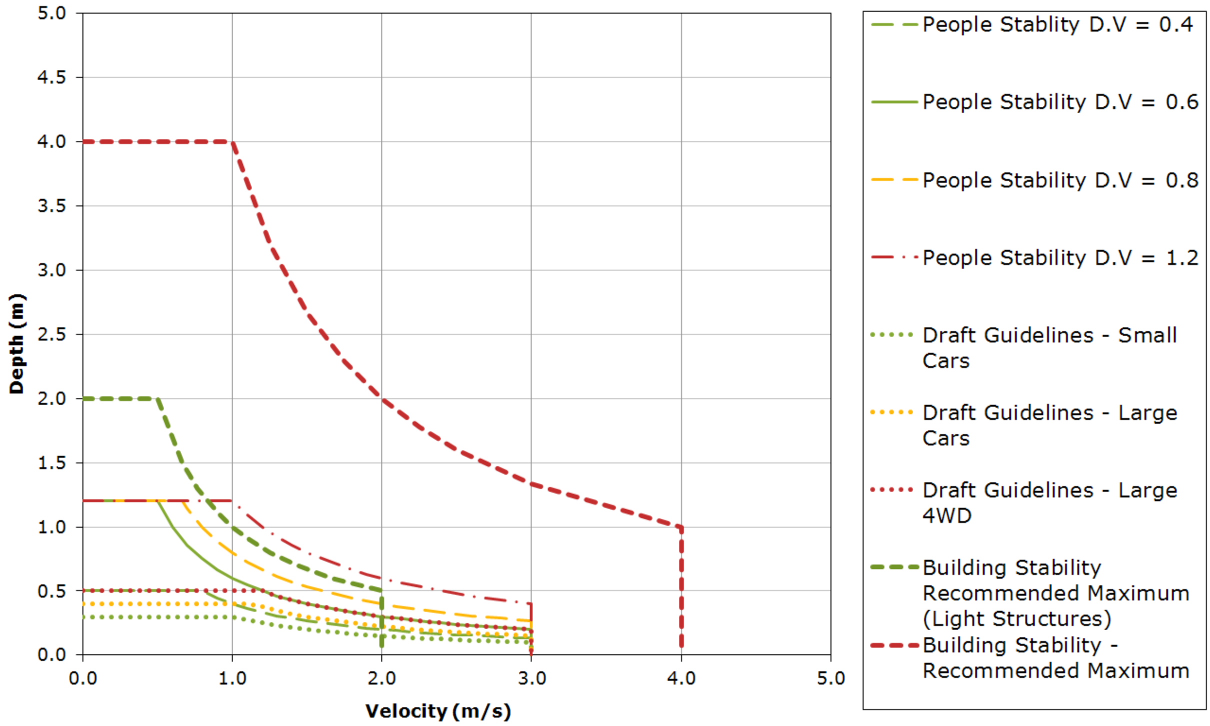


Figure 5-4: Comparison of updated hazard curves

The third observation is that the flood water level that is used as the basis of a hazard depth varies between people and vehicle stability, where the flood depth is referenced to the ground level and building stability where the flood depth is nominally referenced to the floor level.

On a practical level, this would mean that once physical flood behaviour has been quantified in terms of flood depth and velocity, flood hazard could be classified individually for people, vehicles or building thresholds separately. In many instances, this will suit the requirements of specific analyses. For example, if the required assessment is to determine whether a road evacuation route is trafficable for a given flood event, then the vehicle stability threshold curves should be applied. Likewise, if the assessment is to determine which buildings would be suitable for shelter in place during a PMF event, then the building stability thresholds for flood hazard should be used in the analysis.

5.5 General flood hazard curves

When dealing with specific floodplain management or emergency management analysis there may be a clear need to use specific thresholds as described above. However, particularly in a preliminary assessment of risks or as part of a constraints analysis, there is also an acknowledged need for a combined set of hazard vulnerability curves, which can be used as a general classification of flood hazard on a floodplain. A suggested set of curves based on the referenced thresholds presented above is provided in Figure 5-5.

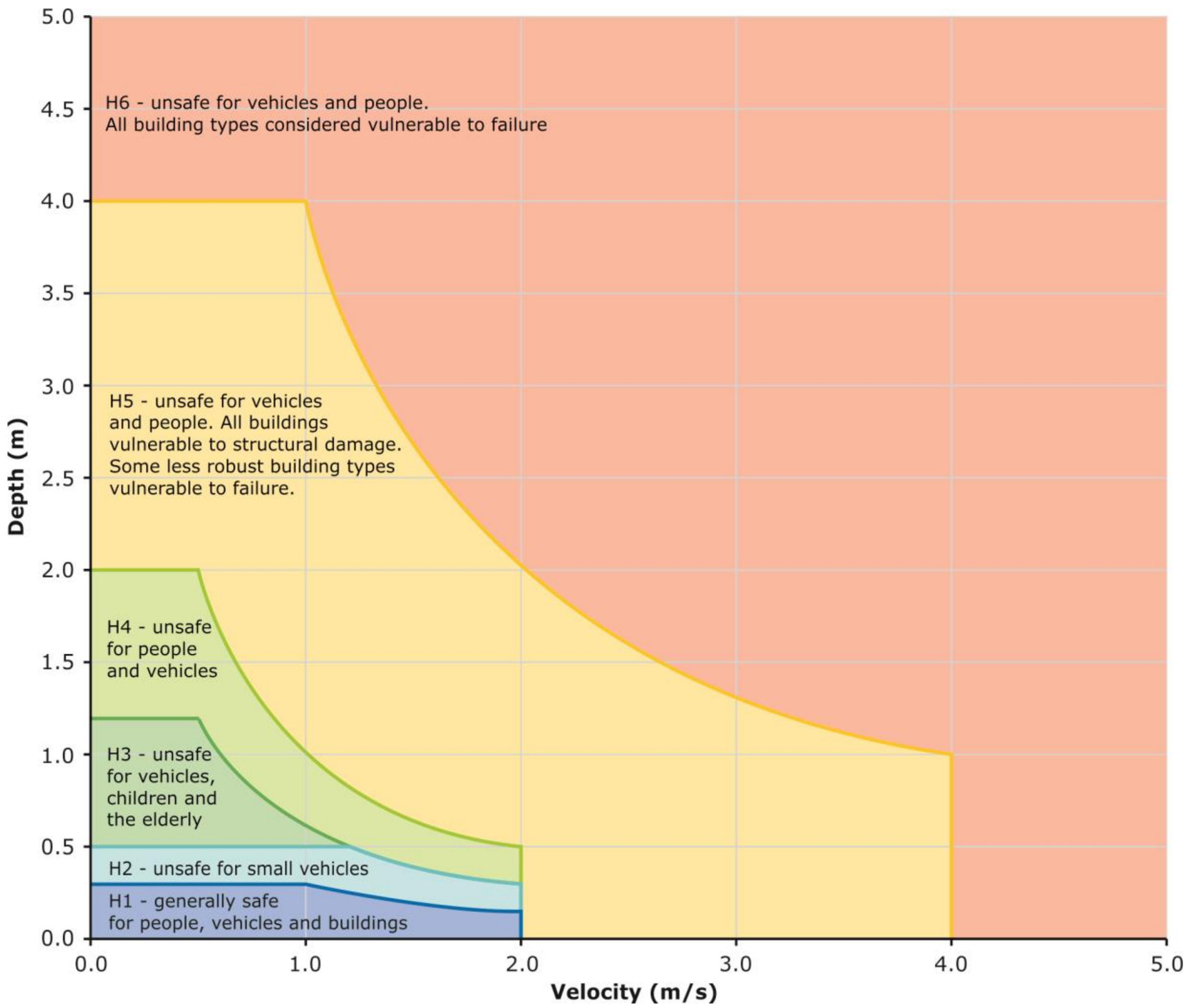


Figure 5-5: Combined flood hazard curves

The combined flood hazard curves presented in Figure 5-5 set hazard thresholds that relate to the vulnerability of the community when interacting with floodwaters. The combined curves are divided into hazard classifications that relate to specific vulnerability thresholds as described in Table 5-1. Table provides the limits for the classifications in Table 5-1

Table 5-1 Combined hazard curves – vulnerability thresholds

Hazard Vulnerability Classification	Description
H1	Generally safe for vehicles, people and buildings.
H2	Unsafe for small vehicles.
H3	Unsafe for vehicles, children and the elderly.
H4	Unsafe for vehicles and people.
H5	Unsafe for vehicles and people. All buildings vulnerable to structural damage. Some less robust buildings subject to failure.
H6	Unsafe for vehicles and people. All building types considered vulnerable to failure.

Table 5-2 Combined hazard curves – vulnerability thresholds classification limits

Hazard Vulnerability Classification	Classification Limit (D and V in combination)	Limiting Still Water Depth (D)	Limiting Velocity (V)
H1	D*V ≤ 0.3	0.3	2.0
H2	D*V ≤ 0.6	0.5	2.0
H3	D*V ≤ 0.6	1.2	2.0
H4	D*V ≤ 1.0	2.0	2.0
H5	D*V ≤ 4.0	4.0	4.0
H6	D*V > 4.0	-	-

Importantly, the vulnerability thresholds identified in the flood hazard curves described in Section 5 above can be applied to the best description of flood behaviour available for a subject site. In this regard, the hazard curves can be applied equally to flood behaviour estimates from measured data, simpler 1D numerical modelling approaches, through to complex 2D model estimates with the level of accuracy and uncertainty of the flood hazard estimate linked to the method used to derive the flood behaviour estimate.

5.6 Timing aspects

Section 0 notes that flood hazard can be influenced by the timing aspects of flood behaviour, including:

- Rate of rise of floodwater;
- Warning time; and
- Isolation during a flood.

Specifically, timing aspects are acknowledged as an important moderator of flood hazard in many emergency management situations (see Section 3.3.3). Importantly, the comparison of the "Time Required" and an estimation of the "Time Available" for evacuation is a pivotal assessment required as part of the evacuation planning process. Similarly, the likely time of isolation of a community is an important aspect of emergency planning for resupply and rescue.

In many instances, particularly when a numerical model is available, flood study analysis provides very detailed quantification of the timing aspects of flood flow behaviour. There are numerous documented methods in the available literature (e.g. SCARM (2000), Tennakoon (2004)), where an attempt has been made to integrate a timing parameter into flood hazard quantification.

While moderating flood hazard using a timing component in the quantification of flood hazard is functionally possible, the interpretation of a hazard mapping, which integrates depth, velocity and timing aspects into a single parameter is more problematic.

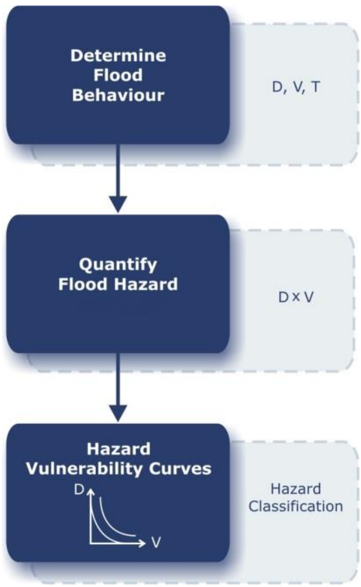
The timing aspects of flood hazard interpretation were discussed at length at the NFRAG Committee meeting of 13 and 14 March, 2014. This discussion concluded that national floodplain representatives were not in favour of an integrated flood hazard parameter quantification combining flood depth, flow velocity and flood timing. In a similar conclusion, modifying of the flood hazard classification using a timing parameter similar to the figure in SCARM Report 73 Section J.3 (reproduced in this report as Figure 2-2) was also not supported by the NFRAG Committee.

Constraints analysis for flood evacuation is being assessed in parallel work being undertaken by Cardno Pty Ltd on examining the use of flood emergency response classifications to differentiate between the severity of the isolation problems of communities during flooding. Timing aspects of flooding are taken into account in this assessment, but are considered separately to but in conjunction with available flood hazard mapping developed based on the flood depth and velocity parameterisation discussed in Sections 5 and 1.1of this report.

6. Flood Hazard Quantification – Practical Considerations

6.1 Overview

Flood hazard quantification is fundamentally a three-step process as illustrated in Figure 6-1. In the first instance, the physical properties of the subject flood (e.g. the defined flood event, PMF, etc.) are quantified. Typically, the core properties quantified will be estimates of flood depth and velocity quite often expressed as time series data. Contemporary practice is to generate estimates of these flood properties using two dimensional, numerical, hydrodynamic modelling techniques. However, simpler approaches to estimate flood parameters for a floodplain may also be valid depending on the local flood behaviour, the type of development at risk to flooding and the quality of data available. The flood behaviour properties can then be post processed to determine estimates of flood hazard.



D=depth, V = velocity, T = time

Figure 6-1: Process for quantifying flood hazard

The second step is to estimate flood hazard as a combination of the physical flood behaviour parameters, velocity (V) and depth (D) as a depth times velocity product (DxV). Typically, the third step in the process would be to classify the hazard against vulnerability threshold curves such as those discussed in Section 5.

6.2 Recommended flood events for hazard assessment

Section 2 identified that SCARM Report 73 (SCARM 2000) did not recommend appropriate design flood events to be considered for flood hazard classification. AEM Handbook 7 identifies that sound floodplain management practice should consider a full range of design flood probabilities. Further to this, there are numerous documented floodplains (HNFMSC, 2006a) where the flood hazard can vary considerably between floods of differing severity, for example between the 1% and 0.5% annual exceedance probability (AEP) flood events.

Based on the review conducted for this report, it is recommended that as a minimum, flood hazard mapping be produced for the design flood event (DFE), a flood smaller than the DFE and the PMF or a representative extreme event. Flood hazard mapping of these events will provide land use planners and emergency managers with an overview of changes in the severity of flood hazard over a range of events.

6.3 Interpreting model results

While the process outlined in Figure 6-1 might appear straight forward, there are subtleties in flood hazard analysis that practitioners need to be aware of. Several important methods of data analysis and interpretation are outlined below.

6.3.1 Calculating flood depths and velocities for analysis

It is important to note that the maximum hazard value during a flood may not occur at the peak flow rate or the peak flood level, but on some combination of D x V during the flood event. High values of D x V, beyond important hazard thresholds, may occur on the rising limb of a flood and are important to be considered in flood hazard assessments. For example, when considering the safety of a flood evacuation route, hazard values above the D x V thresholds for vehicle stability may be exceeded prior to the peak of flood levels. This case is illustrated graphically in Figure 6-2 and Figure 6-3. In this case, the peak flood hazard value occurs at time (1) which is before the peak of the flood at time (2).

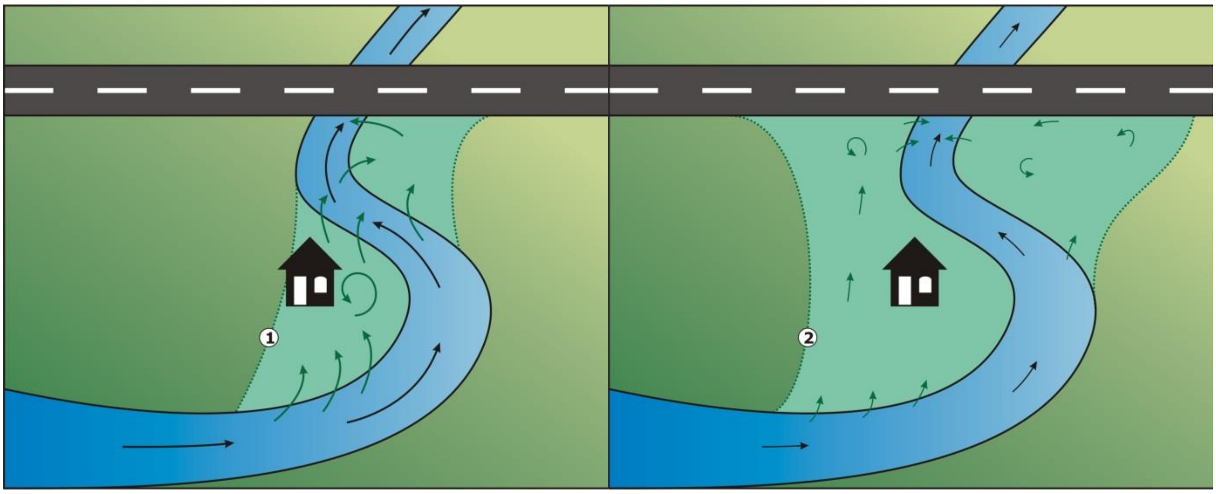


Figure 6-2: Floodplain Case –Time (1) on the rising limb of the hydrograph has higher hazard than Time (2) corresponding to the peak flood level

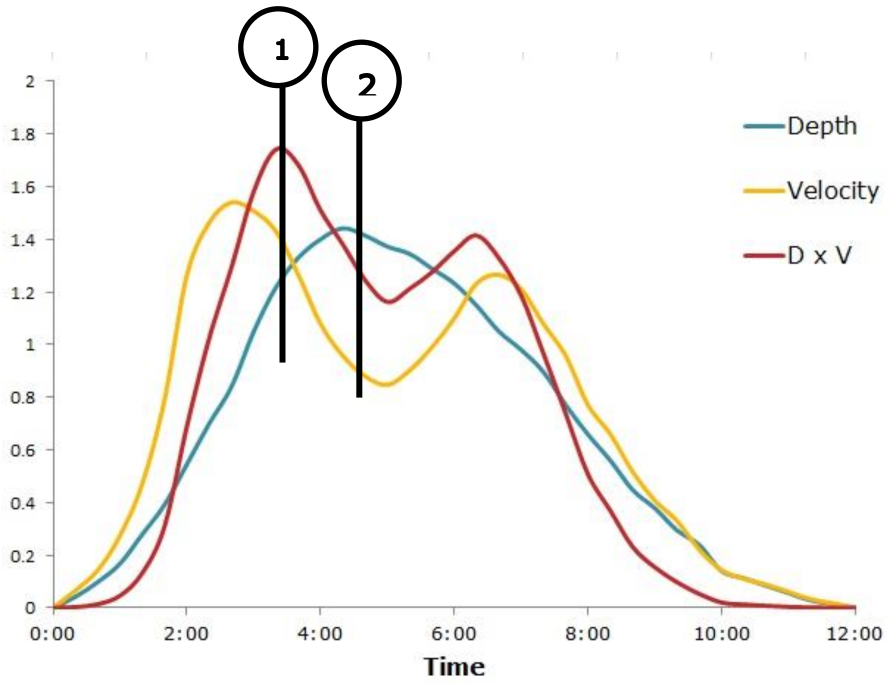


Figure 6-3: Flood hydrographs for the subject floodplain in Figure 6-2

The example as presented reinforces that hazard quantification needs to be undertaken for all time steps during a model simulation, not just at the peak of the flood flow hydrograph or at the time of peak flood level.

6.3.2 Model resolution and velocity estimates

Industry practice when quantifying flood hazard typically involves a simple and literal interpretation of flood behaviour information generated by numerical flood models directly into a flood hazard classification index. Typically, this involves combining the mapped depth (D) and velocity (V) information from a numerical model into a velocity-depth product (D x V) and categorising this product value using curves similar to the process outlined in Section 6.1.

Recent investigations (Mack, 2013; Smith and Mack, 2014) have compared data from physical and numerical models of a subject urban floodplain at Merewether Heights, NSW. Smith and Wasko (2012) used these models to demonstrate some of the inherent uncertainties in a literal interpretation of model results into an estimate of provisional flood hazard.

The Smith and Wasko (2012) physical model (Figure 6-4) was for a 300 m long section of urban floodplain at Merewether Heights in Newcastle, NSW. This model was calibrated to flooding which occurred during the 'Pasha Bulker' flood of June 2007.

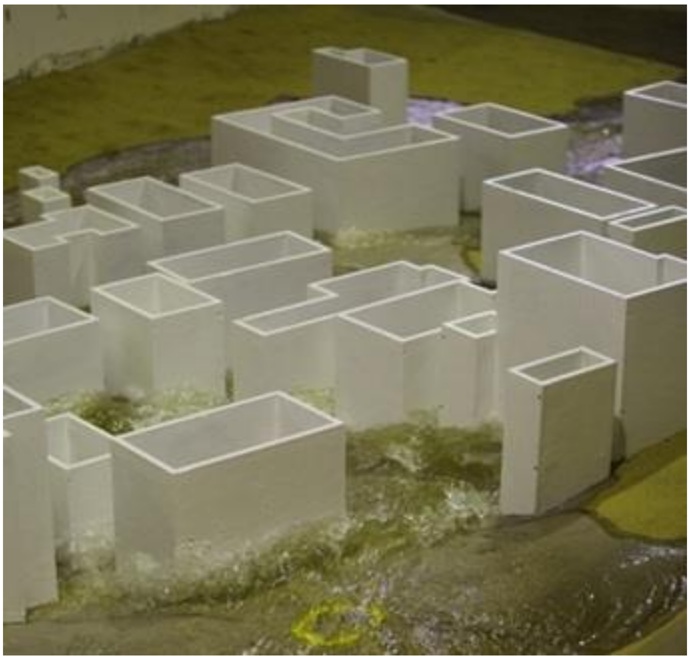


Figure 6-4: Merewether Heights physical model at WRL

A range of numerical models of varying model grid resolutions typically applied in urban areas were developed and calibrated to the available peak flood surface level information from the June 2007 flood. Figure 6-5 presents an example of the raw data, depths and velocities, calculated using a numerical model. A comparison of data was made, with some variability observed in peak water surface levels between model grids, though arguably, any of the peak water level result sets for the various model grids in isolation might pass muster as a 'reasonably calibrated' model.

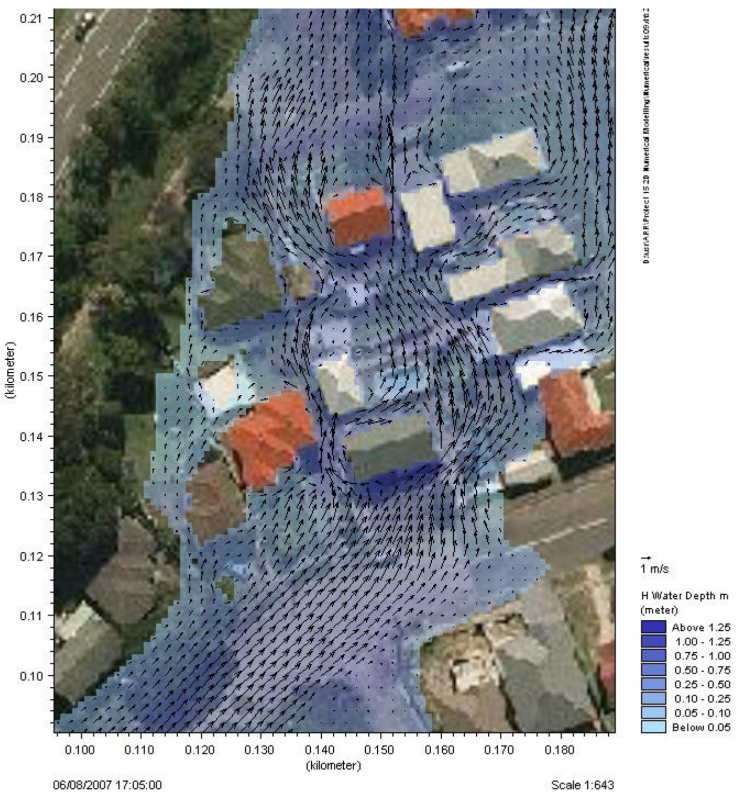
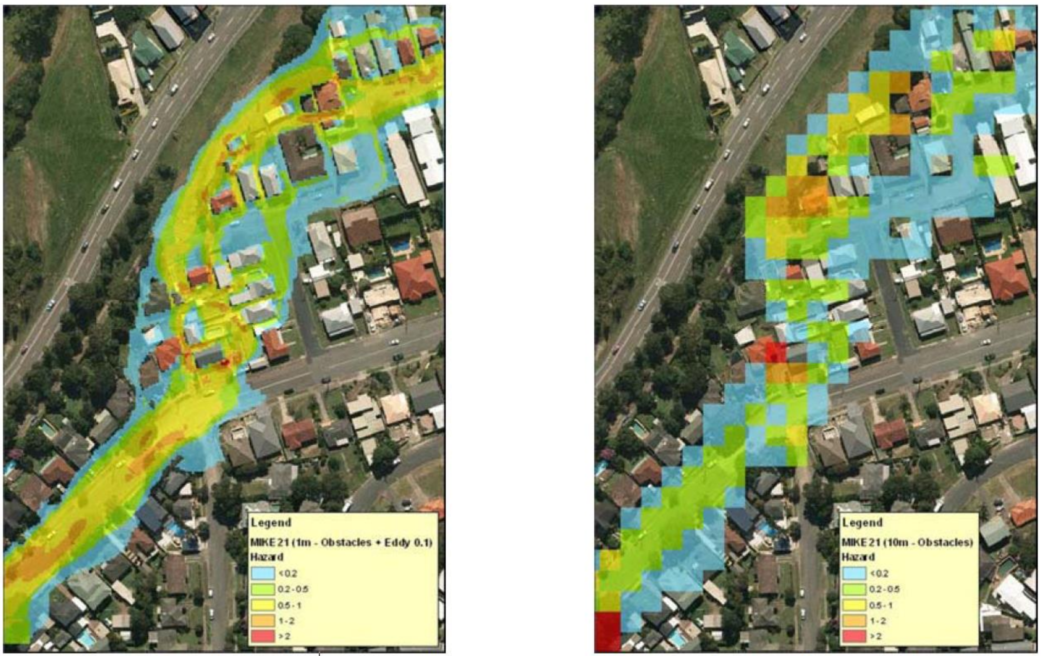


Figure 6-5: Results from the Merewether Heights flood model (Source: Smith and Wasko, 2012)

However, analysis of the mapped 'raw' hazard value (D x V) for a range of model grid resolutions showed the magnitude of predicted flood hazard level varied significantly with grid resolution (e.g. Figure 6-6). While the flood surface slopes and flow depths for each numerical model resolution did not vary significantly with model grid size, the more detailed flow path representation in finer scale model grid topographies was observed to better represent flow behaviour in terms of flow direction and flow distribution across the floodplain when compared to the physical model.



(a) Velocity * Depth Product – 1m grid (b) Velocity * Depth Product – 10 m grid

Figure 6-6: Flood hazard estimates for the June 2007 flood at Merewether, NSW (After: Smith and Wasko, 2012)

These noted differences in provisional flood hazard estimation with numerical model grid resolution were investigated in more detail by Mack (2013) and Smith and Mack (2014). Physical model flow depth and velocity combinations were sampled at various locations (Figure 6-7) around a house on the floodplain that suffered irreparable structural damage during the 2007 flood event, and was subsequently demolished.

Figure 6-7: Sampling locations around house (Source: Smith and Mack, 2014)

Model results for velocity and depth at the locations were plotted against a collated ensemble of flood hazard curves for various numerical grid resolutions and the physical model (Figure 6-8).

The results for hazard value plotted in Figure 6-8 demonstrate that these differences in peak velocity can have potentially serious implications for estimating the impacts to flood inundated residential structures. Figure 6-8 (a to c) shows that the numerical model results for peak velocity generally predict that the flood flows around the subject building structure are below the thresholds for structural damage to brick buildings (BMT WBM, 2012; Clausen and Clarke, 1990; Page, 2000). However, the model results measured at the corresponding locations in the physical model as presented in Figure 6-8 (d) predict local velocities around the subject building at magnitudes that would cause structural damage when compared to the threshold curves for structural damage to brick buildings. Taking into account that the subject building actually suffered significant structural damage in the June 2007 flood, the under-predicted peak velocities produced by the numerical model outputs have provided a non-conservative result that might have significant implications for floodplain planning especially where structural stability under flood conditions is relied upon for safe refuge.

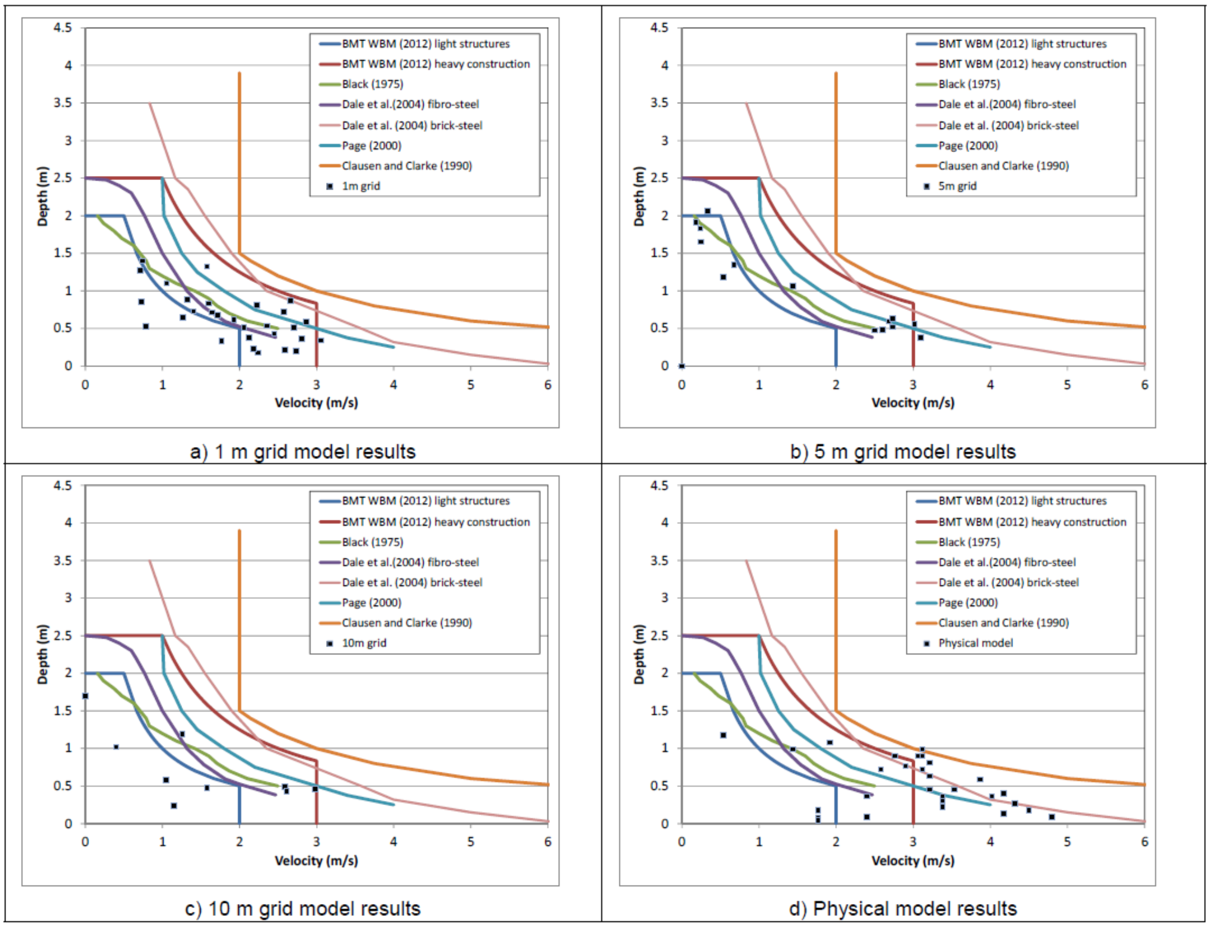


Figure 6-8: Model results for the June 2007 flood in Merewether, NSW, compared to flood hazard curves for residential buildings (Source: Smith and Mack, 2014)

The presented case demonstrates issues with interpreting local velocities from numerical model results. While the presented case is for a 2D model, similar issues are prevalent, perhaps to a larger degree, when interpreting flow local flow velocities from 1D models or indeed from measured data.

6.3.3 Special cases for consideration - levees

It is important to note that in some instances, the flood hazard estimates developed from raw model results need to be carefully interpreted. One particular case is the flood hazard classification of land behind a levee. Levees are typically installed to protect land from inundation that would otherwise be flooded in the levee design event. Flood hazard assessment for land protected by levees requires special consideration. For floods up to the levee design flood, a literal interpretation of flood hazard for the area during a main river flood event up to the design flood magnitude would be that the land is flood hazard free. It is recommended that as a minimum, flood hazard mapping be produced for two (2) floods larger than the DFE including the PMF or a similar representative extreme event. Flood hazard mapping of these larger events will provide land use planners and emergency managers with an overview of changes in the severity of flood hazard over a range of events and provide valuable information about residual risk of the site.

In many instances though, the present level of protection provided by a levee system has considerable uncertainties. These include:

c) Uncertainties in design flood flow rate / level estimation;
d) A lack of appropriate levee maintenance leading to reduction in the level of protection afforded by the levee due to settlement of the levee or degradation of the levee height through vehicle or livestock traffic;
e) Uncertain geotechnical integrity through lack of appropriate embankment design and construction;
f) Poorly designed local drainage behind the levee creates a local flooding problem;
g) A levee design that, when embankment failure or overtopping occurs, floods the area behind the levee with high hazard flood waters;
h) Isolation issues when flooding around the levee embankment create an 'artificial' low flood island.

When assessing the hazard for areas protected by levees, there is a need to address the residual risks posed by the uncertainties listed above. AEM Handbook 7 provides further reference on the considerations for levee design and the problems they potentially introduce.

7. Conclusions and Recommendations

This report has documented the findings of a review of flood hazard quantification and classification.

The report has found that the general concepts for quantifying and classifying flood hazard in SCARM Report 73 Appendix J SCARM (2000) remain sound, however, the information available to describe flood hazard thresholds has expanded considerably since that document was published.

An international literature search building on the findings of the Australian Rainfall and Runoff review process has been used to define flood hazard thresholds based on people stability, vehicle stability and building stability. This report has found that hazard classifications based on these stability thresholds are suitable for flood hazard quantification and analysis to underpin the floodplain management process.

Flood hazard threshold curves are provided for people stability, vehicle stability and building stability separately. Where a particular analysis is focussed primarily on one of these aspects, e.g., evacuation route analysis for vehicle based emergency evacuation, then the individual threshold curve specific to that analysis should be used.

Where a constraints analysis for a broader scale investigation is required, a consolidated set of threshold-based curves has been provided for this style of hazard classification.

Timing aspects contributing to flood hazard are acknowledged in the report as being an important aspect of flood hazard quantification. However, the recommendation of this report is that the timing aspects of flood behaviour be quantified separately to the hazard caused by the flood depth and velocity of the floodwaters. Consideration of timing aspects of flood behaviour more readily feed into the parallel work being undertaken by Cardno Pty Ltd on examining the use of flood emergency response classifications to differentiate between the severity of the isolation problems of communities during flooding.

The report has reviewed current practice for quantification of flood hazard using a range of flood behaviour estimation techniques and made suggestions to assist practitioners interpret flood hazard from these data sets. Importantly, the vulnerability thresholds identified in the recommended flood hazard curves can be applied to the best description of flood behaviour available for a subject site. In this regard, the hazard curves can be applied equally to flood behaviour estimates from measured data, simpler 1D numerical modelling approaches, through to complex 2D model estimates with the level of accuracy and uncertainty of the flood hazard estimate linked to the method used to derive the flood behaviour estimate.

The information in this report has described a sound basis for quantifying flood hazard. The information presented in this report can be used as the basis of a technical guideline to support AEM Handbook 7.

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