RiskScape: Flood fragility methodology

NIWA Technical Report: WLG2010-45
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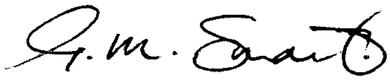

Dr Graeme Smart **Dr Andrew Laing**

Executive summary

This report was commissioned by the New Zealand Climate Change Research Institute, Victoria University of Wellington for a Hutt Valley case study on vulnerability to increased flood risk with climate change and funded by the Foundation for Research, Science and Technology under contract VICX0805 *Community Vulnerability and Resilience*.

Flooding accounts for 70% of all natural hazard related damages in New Zealand (Department of Prime Minister and Cabinet, 2007). This report summarises development of the methodologies and current approaches incorporated within the RiskScape model to define the damage to property, infrastructure and people due to flood inundation events. Depth-damage functions, also called stage-damage curves or fragility curves, are the most common method to estimate potential direct damage costs. Fragility curves typically relate the percentage damage (relative to replacement cost) for a variety of elements such as buildings, cars, household goods, relative to flood characteristics such as inundation depth, velocity or duration.

RiskScape is a new tool, being developed jointly by the National Institute of Water and Atmospheric Research Ltd (NIWA) and the Institute of Geological and Nuclear Sciences (GNS Science). The prime goal is to develop an easy-to-use decision-support tool that converts hazard exposure information into likely consequences for a region, such as damages and replacement costs, casualties, disruption and number of people affected. Consequences and risk for each region presented in a common platform across all natural hazards can then form the basis of prudent planning and prioritised risk-mitigation measures that link directly to the severity of the risks.

The methodologies outlined in this report are based on the RiskScape flood module, developed by NIWA and current as of July 2010 but are liable to future change as ongoing research and further survey data refine and extend the approaches.

1. Introduction

1.1 Overview of this report

This report summarises the development of the methodologies and current approaches incorporated within the RiskScape model[1] to define the damage to property, infrastructure and people due to flood inundation events.

This report has been specifically prepared for the New Zealand Climate Change Research Institute at Victoria University of Wellington as input to a Hutt Valley case study on vulnerability to increased flood risk with climate change. It is largely based on an internal working document that summarises the development of the approaches adopted within RiskScape to translate flood and tsunami inundation hazard characteristics into resulting damage.

The methodologies outlined in this report are current as of July 2010 but are liable to future change as ongoing research and further survey data refine and extend the approaches.

1.2 An introduction to flood fragility

Flooding accounts for 70% of all natural hazard related damages in New Zealand (Ref. please). Depth-damage functions, also called stage-damage curves or fragility curves, are the most common method to estimate potential direct damage costs. Fragility curves typically relate the percentage damage (relative to replacement cost) for a variety of elements such as buildings, cars, household goods, relative to flood characteristics such as inundation depth, velocity or duration.

Fragility functions are typically based on either:

- empirical curves developed from historical flood and damage survey data or
- synthetic functions (hypothetical curves) based on expert opinion developed independently from specific flood and damage survey data.

Both methods have their advantages and disadvantages (see Middelmann-Fernandes, 2010). RiskScape uses a combination of both as it has been found that synthetic damage curves calibrated against observed flood damage gave the most accurate results (McBean et al., 1986). As damage to buildings typically makes up the most significant proportion of direct-damage costs, the initial project focus was on buildings and their contents, but progress in other categories is also being made. A summary of flood fragility functions that have been developed or are in progress are listed in Table 1.

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[1] http://www.RiskScape.org.nz/

Table 1 **Existing flood fragility functions used within RiskScape**

Type of Fragility Function	Exists
Buildings	✓
Content	✓
Injuries	✓
Fatalities	✓
Displacement	✓
Vehicles	✓
Road network	✓
Business disruption / functional downtime	✓
Loss of income	✓
Water supply network	✓
Sewerage network	✓
Storm-water network	✓
Traffic disruption	
Telecommunication network	
Electricity network	
Crop damage	
Cost of emergency and relief	
Disruption of public services	
Health impacts	

The starting point in developing fragility functions is to identify the most vulnerable elements of the asset. For example, in terms of buildings: walls, floors (particularly plasterboard and chipboard), floor coverings, built-in kitchen units and electric appliances are normally the most vulnerable building and contents components. Ideally these elements would be specified directly within the input parameters of the fragility function. However, information on the specifics of these elements for each building is a major limitation. For example, a very detailed asset database would be required to contain all the required information on elements such as floor coverings and built-in kitchens. The only way to obtain this level of data is through individual household surveys, which are too expensive to conduct for large areas with many buildings. Hence, the inventory is developed to hold only basic information about the type of building, which in return means that the fragility functions are limited to basic generic parameters, or to adopt surrogate relationships using these basic parameters.

Prior to commencement of the RiskScape project in 2004, little work had been conducted in New Zealand to collect damage information and develop New Zealand specific fragility curves. Most of the curves in this study have been developed through a thorough review of international studies (Table 2) and consideration of how these studies apply to the housing attributes and flooding characteristics in New Zealand.

Table 2: Summary of key international studies used to inform the development of flood damage fragility curves in New Zealand.

Country	References
US	Usace, 1992, 1996, 1998; FEMA 2003
UK	Parker et al., 1987; Penning-Rowsell et al., 1992; Penning-Rowsell & Chatterton, 1997; Penning-Rowsell et al., 2003; Penning-Rowsell et al. 2005; Proverbs & Soetanto, 2004.
Germany	Klaus & Schmidtke, 1990; Beyenne, 1992; IFB-Braschel und Schmitz 1995; Rother et al., o.J; MURL, 2000; IKSR, 2001; Staatliches Umweltamt Siegen, 2001, Reese, 2003
Netherlands	Kok et al., 2005
Norway	Sælthun, 2000
Australia	NHRC, 2000, 2000a
Italy	De Lotto & Testa, 2002
Japan	Kato & Toriil, 2002

Since the initial set of fragility functions were derived for New Zealand, three major field and postal surveys have been undertaken: after the 2004 Lower North Island Flood and after the March and July 2007 Northland Floods. These have been used to refine and adjust the initial fragility curves.

2. Building-related damages

2.1 Building fragility functions

2.1.1 Damage states

Floods may cause structural damage to a building, particularly where inundation reaches or exceeds the elevation of the floor. Damage to walls and floors can be considerable, expensive to repair, and the structure may be uninhabitable while it is dried out and repairs are undertaken. Where significant structural damage occurs, partial or full collapse may occur which can also lead to injury or fatalities.

Direct building damage is typically expressed in terms of: cost to repair ($), damage ratio, i.e. repair cost relative to replacement cost or as a damage state. Within RiskScape, five damage states are adopted, and a broad description of the damage state classification is given in Table 3.

Table 3: Summary of damage states, damage description, and damage ratio used within RiskScape.

Damage state	Description	Damage ratio
DS0	Insignificant	0–0.02
DS1	Light—Non-structural damage, or minor non-structural damage	0.02–0.1
DS2	Moderate—Reparable structural damage	0.1–0.5
DS3	Severe—Irreparable structural damage	0.5–0.95
DS4	Collapse—Structural integrity fails	> 0.95

For each damage state, different repair actions would be required to restore the structure to its pre-flood condition. For example, DS1, which represents non-structural damage, is likely to require only repair of interior walls that have been saturated, and possible superficial external damage (e.g. broken windows). On the other hand, DS4 represents severe damage to the structural system itself, which would require partial or complete demolition of the structure and replacement. For each of these damage states a damage ratio is also defined and summarised in Table 3.

2.1.2 Factors influencing flood-related building damage

The level of damage to buildings caused by floods depends on various factors, the most important being the flood characteristics (primarily water depth, water velocity, inundation duration), and the building characteristics (type of structure, material, etc.) (Middelmann-Hernandes, 2010; FEMA, 2003). The likelihood of flood depths above 5m in populated areas in New Zealand is limited. Hence, all fragility functions developed have an upper limit of 5m above floor height.

Essential input parameters based on information that is typically easily available about a building[2] are: construction type, wall cladding, building height or number of storeys, and construction age (see also Roos, 2003, Kok et al., 2005. NHRC, 2000).

Floor type has also been identified as a key parameter for New Zealand buildings. Prior to 1960, timber floors were the most common types. Between 1960 and 1980 chipboard flooring was prevalent and post 1980, slab / concrete floors low to the ground dominate residential dwelling floor types. According to Bengtsson et al. (2007) concrete slabs now occur in over 92% of all new detached residential housing. The total percentage of concrete foundations is estimated to be approximately 27% of the total residential building stock in New Zealand. Timber and concrete floors are both comparatively flood resistant, provided that timber floors have been treated with appropriate preservatives (Allianz, 2006). Chipboard flooring usually needs replacing after being soaked.

Detailed knowledge of the floor / foundation type for individual New Zealand buildings is not known or contained within the Quotable Value (QV) building dataset used to derive the majority of the specific building information used within RiskScape. Instead building age has been used a surrogate for floor type.

Several international studies including FEMA (1997), USACE (1993), Penning-Rowsell & Chatterton (1977), show that inundation damage also depends on the number of storeys. For a specific flood depth, the damage ratio for a single storey building is usually higher than for a two storey building.

The suite of fragility curves developed for residential and commercial buildings are summarised in Figure 1 and discussed further, in terms of structural type, in the remainder of this section.

[2] In RiskScape the Quotable Value building database is used as the primary building asset information source.

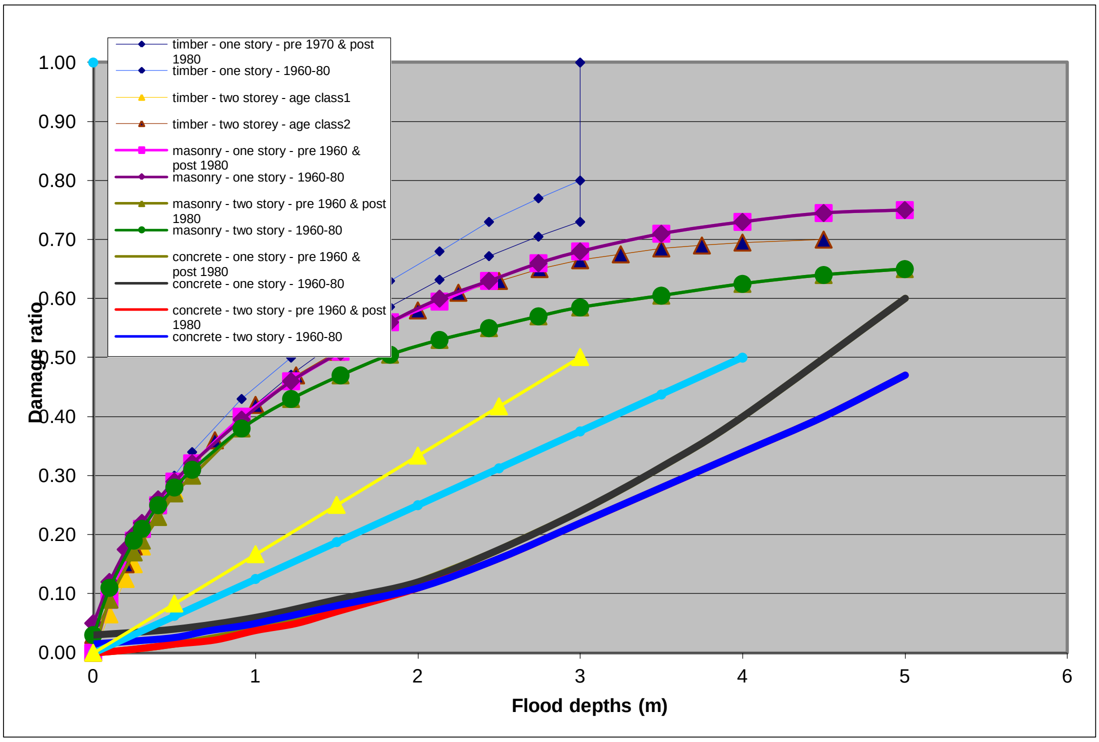

Figure 1 Flood fragility curves for various building types, with inundation depth above the floor level (m) along the horizontal axis and average damage ratio along the vertical axis.

2.1.3 Timber / weatherboard buildings

Fragility curves were developed for timber / weatherboard housing and the same generic criteria were then used to develop similar curves for brick / masonry and concrete dwellings (see next sections). Based on the previous section, four curves were developed based on the number of storeys and age of the property:

- Number of storeys:
  - One
  - Two or more
- Age of property:
  - Age class 1 (pre-1960 & post-1980)
  - Age class 2 (1960–80)

The pre-1960 or post-1980 classification (Age class 1) is assumed to have either timber or slab concrete flooring respectively, with the 1960–1980 classification (age class 2) assumed to be chipboard flooring.

As floors are affected immediately after a flood enters a building, the different fragility curves shown in Figure 1 vary in the lower (shallower water depth above floor level) part of the curve, but have the same general shape in the upper part (in deeper water levels). As chipboard floors are not resistant to water, it has been assumed that the slightest contact causes substantial losses. Damage (5%) is assumed as soon as water comes in to contact with the underside of the chipboard flooring (capillary processes will result in moisture penetration above the underside of the flooring). For timber and or concrete flooring, damage commences as water enters the inside of the house

2.1.4 Brick / masonry residential dwellings

Brick and masonry houses in New Zealand normally have a timber frame and plasterboard wall linings on the inside. Despite the brick or masonry material they tend to be highly vulnerable to flooding. Hence, the fragility curves developed are similar to those for timber framed buildings.

The brick / masonry curves were derived from the timber / weatherboard ones outlined above and adjusted to account for the following aspects:

- A lower maximum damage is likely due to the slightly better flood resistance of the brick / masonry veneer (Dale et al., 2009).
- Based on an adapted maximum damage ratio of 0.75, for a flood depth of 5m, total damage of this building type from physical contact with water is also unlikely.
- The probability that a brick or masonry house will float is also very low. Black (1975) stated that a water depth of 5.2m would be required for a 1.5 storey brick-veneer house to become buoyant. Dale et al., (2009) concluded that Australian houses, which are similar to New Zealand's, are much heavier than those assessed by Black, and hence would require even larger depths to become buoyant.

As before, four fragility curves are available for brick or masonry residential buildings based on single or multiple storeys and the age of the property (Figure 1).

2.1.5 Concrete and reinforced masonry residential dwellings

Concrete buildings are assumed to be more flood resistant than the other two categories. It is assumed that a concrete or reinforced masonry building type has no plasterboard wall linings or any other kind of additional lining that is vulnerable to inundation damage. FEMA (1993) classified concrete as highly flood resistant and recommended material in flood prone areas. Based on international literature, the shape of the fragility curve is assumed to be different from the previous two building types (Schwarz & Maiwald, 2008; Yamin, 2010) with only minor damages expected with low inundation depths. As before, four fragility curves based on the single or multiple storeys and age of property have been defined (Figure 1).

2.1.6 Commercial buildings

It has been assumed that the residential dwelling fragility curves can also be applied to commercial buildings such as offices, schools, etc., as they normally have a similar structure and use similar materials. Studies in Germany have shown that the average flood damage for residential and commercial buildings was similar (Reese, 2003). Commercial buildings usually have larger ceiling heights (average 3m), but in terms of damages to the building structure the difference is not expected to be significant.

2.1.7 Industrial and warehouse buildings

Industrial and warehouse buildings are quite different to residential ones, most constructed with a steel portal frame structure and cladding. Such structures are considered moderately vulnerable to flood induced structural damage (i.e., excluding contents and fixtures). In deriving the fragility curves for industrial buildings it was assumed that:

- The average maximum damage ratio won't exceed 50%.
- A linear relationship between water depth and damage ratio was adopted due to very limited literature and information about the behaviour of these types of buildings.
- Large proportions of industrial buildings are hall type constructions and have average ceiling (wall) heights of around 4m.

Two fragility relationships were developed: one for an average wall height of around 4m, and a second for a 3m high ceiling height.

2.1.8 Influence of flow velocity on building damage

Flow velocity is a major factor that can aggravate structure and content damage (USACE, 1996). The relationship between velocity and damage has been addressed in a number of studies (Black, 1975; Clausen and Clark, 1990; Smith, 1994, Dale et al., 2004) Based on these studies a methodology was developed to account for enhanced damage due to velocity.

Black (1975) concluded that for a static water depth, the maximum bending moments (the resistance of a member to bending; measured in terms of force times distance) for timber framed houses produced by hydrostatic and dynamic pressure occurs at depth of 0.9m (with no flow velocity). However, if water enters the house to the same level as outside, the hydrostatic pressure will equalise on both sides of the wall. The maximum bending moments then occur with a water depth of 2.2m and a velocity of 1.5m/s or 1m and a velocity of 2.4m/s.

Dale et al. (2004) reported that Australian timber and fibro houses could fail (moved off of their foundation) with a flow velocity as low as 0.4m/s if the water depth is

2.4m or greater. Based on these approaches a combination of velocity (*V*) and water depth (*D*) depth (i.e., $V \times D$) has been used to define critical velocities for the above building types. Depending on the value of *VD* we assume three damage states:

- Damage only caused by water depth.
- Additional damage due to velocity.
- Collapse of building.

Figure 2 shows these thresholds for timber / weatherboard type buildings.

2.1.9 Other factors influencing building damage

Scouring of foundations, debris entrained within flood flows, contamination, duration of flooding, time of occurrence, and post-event aeration of a flooded building are also important factors in the overall level of damage that occurs.

The duration of flooding is important, for instance when calculating production losses and it can also influence direct damages. USACE (1996a) argue that duration may be the most significant factor in the destruction of building fabric. Penning-Rowsell et al. (2003) assume increased damages from longer duration of flooding e.g., for mortar, drains, timbers, plasterwork and tiles. The contents and loads of flood water can also influence and increase damages significantly, particularly contamination by oil, but also sediment load and saltwater (Reese, 2003). However, due to the paucity of information, incorporating the effects of these parameters is extremely difficult and they are not included within the fragility functions at this stage.

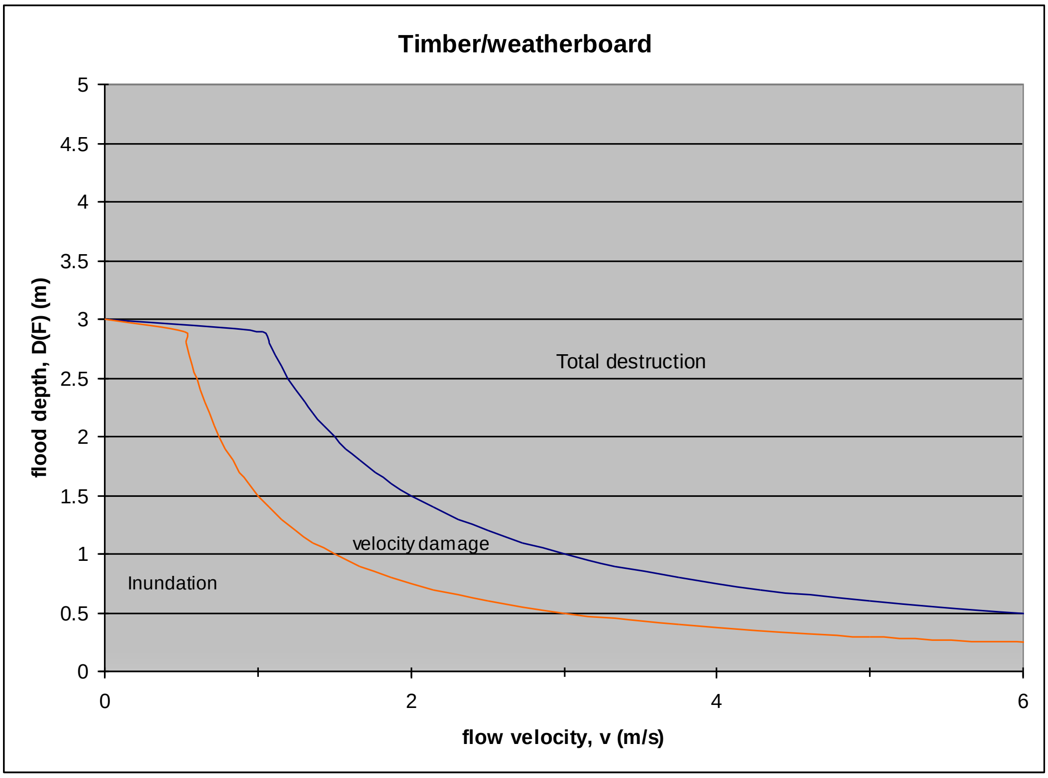

Figure 2: Inundation depth (D) and velocity (V) thresholds for: (a) onset of damage due to water velocity; and (b) total destruction, of timber / weatherboard buildings.

2.1.10 Verification of fragility curves with post-event survey data

Figure 1 shows the set of inundation fragility curves for the various building types combined in one graph. These functions have been verified and refined accordingly after post-event surveys which were conducted after major flood events in 2004 and 2007.

Figure 3 shows how some of the survey information compares with the derived fragility curve for timber and weatherboard housing. This shows some scatter in the survey data but does provide some assurances that the fragility function appears to adequately represent the average damage for a given inundation depth above the floor level. Further work is ongoing to incorporate the potential variability in damage response to flood depth by potentially introducing upper and lower bounds or by moving to a probabilistic approach.

Figure 3: Comparison of fragility model and loss data for timber houses. Flood depth is relative to the floor level.

2.2 Building contents damage

2.2.1 Residential buildings

The damage to contents within a building can often be significant and of the same order as direct structural damage. Building contents comprise both mobile equipment (furniture, books, etc.) and fixtures (carpets, furnishings, lights, etc.).

The assumption has been made that private contents in New Zealand properties are similar for similar socio-economic conditions as in other industrialised countries. The German flood damage database HOWAS has shown that the damages are similar on each storey of a property (see Reese, 2003; Pflügner, 2001). Accordingly, one fragility curve has been developed based on depth above floor level which can be applied to each storey separately.

A 100% damage level for contents is unlikely as some items (such as pots, plates, cutlery, etc.) are often still usable after a flood event. Hence, the defined maximum damage is assumed to be 95%.

Around 85% of household goods are located within 1.5m of floor level, with a significant proportion below 0.5m (carpets, furniture, fridges, etc.). For single storey buildings, if inundation reaches a level of 1.5m above floor depth most of the household inventory is already affected, with an assumed maximum damage of 95% reached with an inundation height of 2m above the floor. As content damage only occurs when the water enters the building, knowledge about the buildings floor height or level is required. This information however is not usually available. Hence, floor heights/levels are based on survey results, using building age as a proxy as follows:

Construction date	Floor height above ground
Pre 1900	450 mm
1900-30	630 mm
1930-40	610 mm
1940-60	740 mm
1960-80	630 mm
Post 1980	520 mm

For two or multiple storey buildings, the absolute content damage is highly dependent on the available floor area in the upper storey and the distribution of household goods over the storeys. However, the relative damage is normally similar, and that is why the same fragility function can be applied.

RiskScape derives the percentage of floor area in the upper floors. This enables split levels or where the second storey floor area is only a fraction of the ground floor area. For example, if the average number of storeys is 1.3, the assumption is that the floor area of the second floor is 30% of the ground floor. The spread of contents is assumed to be based on floor area. For this example it would assume that 77% of the contents were on the ground floor and 23% on the upper floor. The content fragility curve is shown in Figure 4.

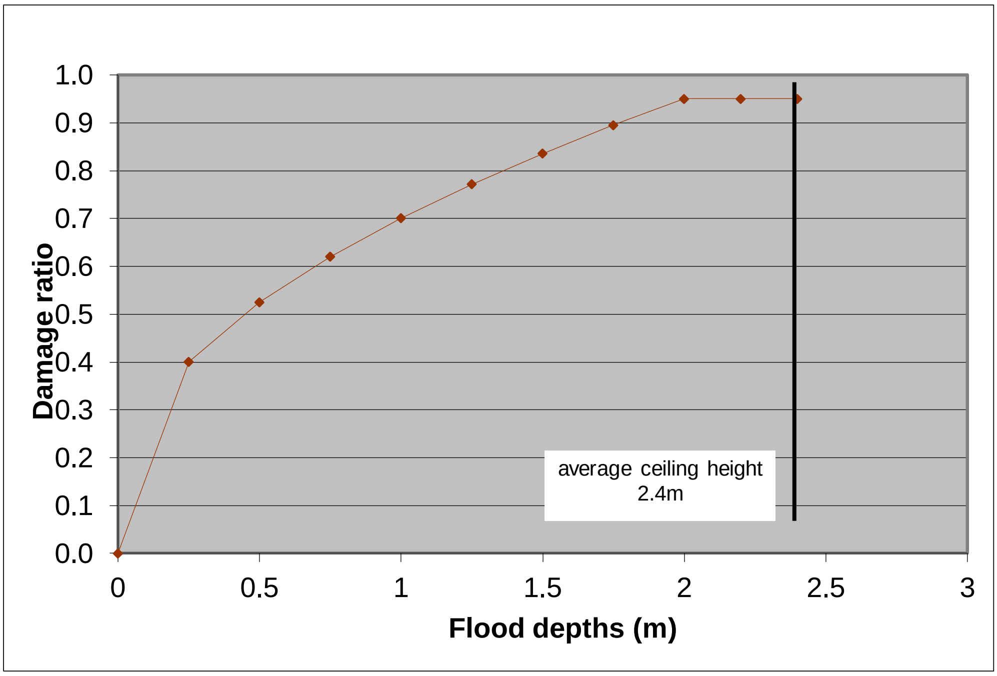

Figure 4: Content fragility curves for residential buildings

2.2.2 Commercial buildings

Separate fragility curves are used for the contents and equipment in commercial and industrial buildings or warehouses (see next section). The basic assumptions are similar as for the residential content fragility curves, the only difference being that commercial buildings typically have a higher average floor to ceiling height (around 3m). It is assumed that the maximum damage will be reached at about 2.4m.

The commercial category includes office type buildings, retail shops as well as public facilities. However, little information exists on potential flood depth-damage relationships for different types of retail companies and public facilities (and it is likely to be highly variable). Hence, fragility functions from German studies have been used as a starting point (Reese, 2003; Pflügner, 2001). At present within RiskScape they have been incorporated into a commercial category where the damage relationship is similar to that for the residential inventory. However, as the amount of cabling and electronic equipment in an office, or stock in a retail store, is typically higher than a residential property, the commercial fragility curves assume a damage ratio of 5% as soon as water levels exceed the floor level.

2.2.3 Industrial buildings

The industrial building contents fragility curve is mainly suited for mid-size manufacturing buildings. For associated offices the commercial fragility curve is used while large factories need to be treated separately. As the vertical distribution of building content is dependent on the floor to ceiling height, two different fragility curves were developed, one for "ordinary" industrial buildings and one for warehouse / supermarket structures.

As there is the potential for huge variation in building contents within this category the description of an average damage is quite difficult. Hence a simple linear fragility curve was developed. Further work is planned to differentiate this category into different sectors.

2.2.4 Influence of flood warning

A good flood warning system and sufficient lead time can reduce the damage to building contents, especially those contents that can easily be shifted (Penning Rowsell & Green, 2000; Smith & Ward, 1998; Smith, 1998; Penning-Rowsell et al., 2005). If a second (or escape) storey is available where building contents can be moved to, this along with suitable warning and indeed very little lead time, can make a substantial difference to the level of content damage. However, the post-event surveys conducted to-date also revealed that residential property owners with only a single floor can also make a substantial reduction in the level of content damage when a flood warning is given. The data collected during these post-event surveys also show a clear correlation between the flood warning lead time and the repair costs (or damage ratio respectively).

Based on these survey results, a set of four fragility functions for **residential content** were developed. Due to the limited data no “escape storey” functions could be developed for more than 1 hour warning lead times. The four functions are:

- Residential content damage without an “escape storey” and less than 1 hour flood warning lead time.
- Residential content damage with an “escape storey” and less than 1 hour flood warning lead time.
- Residential content and flood warning lead time between 1–6 hours.
- Residential content damage and flood warning lead time > 6 hours.

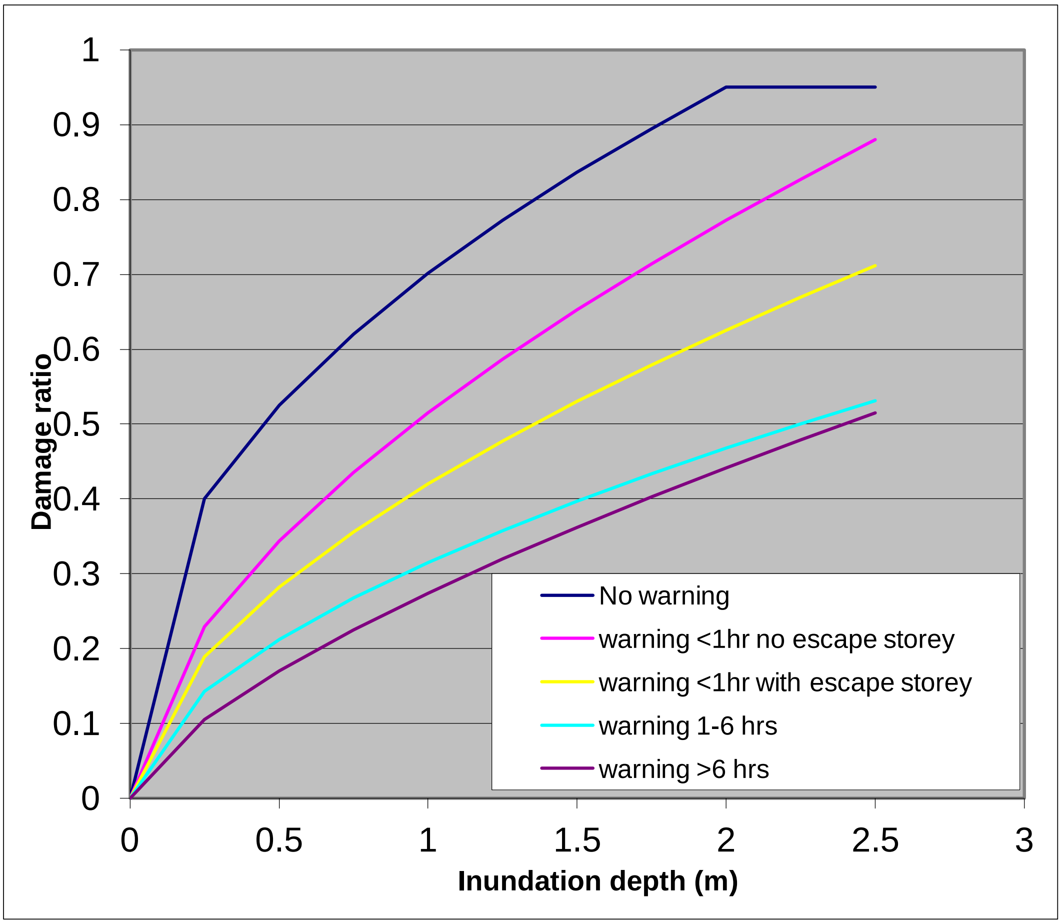

Figure 5: Content fragility curves for residential buildings for different warning lead times

Due to the lack of data, average damage reduction values from the above sources are also currently used for commercial and industrial buildings. For commercial buildings a 1%, 5% and 10% percentage content damage reduction was assumed for the three warning lead time categories. Industrial buildings have primarily heavy machinery and less movable objects, so that the damage reduction is assumed to be lower (0%, 2% and 4% (Reese, 2003).

3. Displacement and disruption

3.1 People displaced—residential property

Displacement time is normally defined as the average time (in days) which the building's occupants typically must operate from a temporary location while repairs are made to the original building due to damages resulting from a hazard event. The displacement time may be shorter than the repair time, because minor repairs can also be made while the occupants are in the building.

The only existing approach that was found in the literature concerning displacement time estimates is from the US / FEMA (FEMA, 2001). The estimation is based on a logarithmic correlation between the building damage and displacement time. It assumes that no displacement occurs if the building sustains less than 10% damage. If the (estimated) building damage is greater than 10%, the displacement time is scaled between 30 and 365 days using a logarithmic function. It assumes that even minor repairs within an affected area will take at least 30 days to complete. The maximum displacement time is one year.

However, our post-event survey data shows an exponential trend and also a slightly lower displacement / building damage threshold of 8%. Based on the post–event survey data a function was derived to estimate the displacement time for DS1 and DS2 damage states. For DS3 and DS4, a displacement time of 365 days is assumed (FEMA, 2001). Should the flood be a large event with more than 500 damaged buildings, the displacement time for DS3 and DS4 damage states increases to 18 months.

Displacement could also occur due to the disruption of critical infrastructure, such as power or water outage. To date this has not yet been included within the RiskScape flood fragility functions.

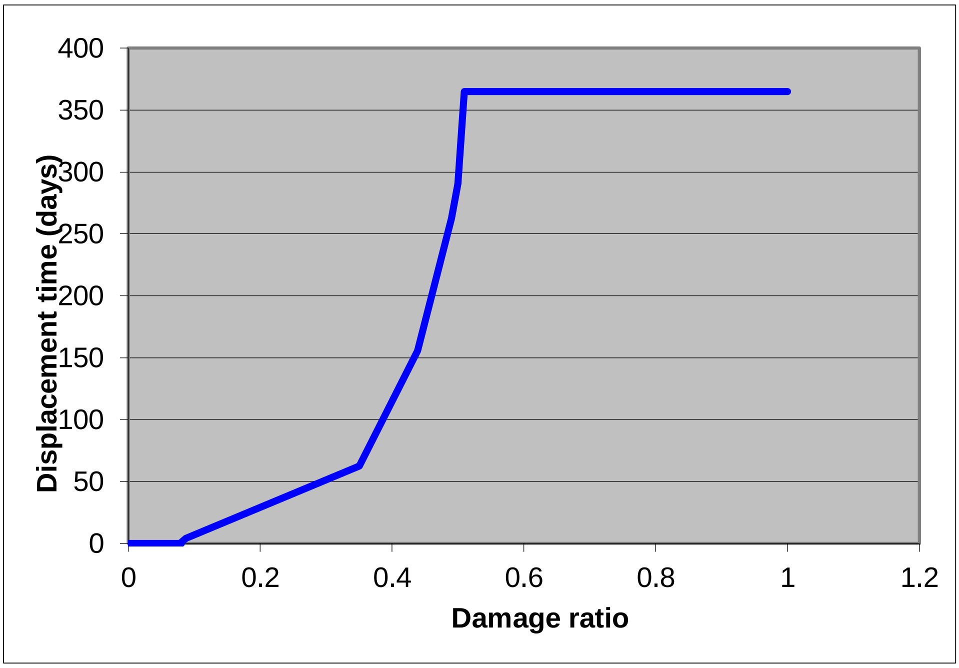

Figure 6: Displacement fragility curve for residential buildings

3.2 Business disruption—functional downtime

Functional downtime is defined as the time (in days) a public facility, commercial or industrial business can not operate due to direct damage following a disaster. What is relevant is the time the business is disrupted, not the duration of any potential relocation. A business may have to relocate for a period of time but may resume service during the relocation.

As for displacement time, the building's damage is used as an indicator for the functional downtime. It is estimated that if the building damage is less than 10%, then one day of functional downtime occurs for each 1% of building damage (FEMA, 2001). However, if the building damage exceeds 10% the downtime estimates are scaled between 10 and 45 days. The assumption is that the maximum functional downtime is 45 days.

The post-event survey following the 2004 Manawatu / Hutt Valley floods contains information concerning business disruption. The average duration of business disruption was 2.9 days, (with a minimum disruption 0.5 days, a maximum disruption of 20 days, and a standard deviation 3.7 days). The analysis of the data showed a correlation between the building / content damage and business disruption with buildings with only minor damage experiencing disruption for less than 4 days, while more severely damaged building had a disruption between 5–20 days. This helped validate the above assumptions and a logarithmic function was implemented into RiskScape.

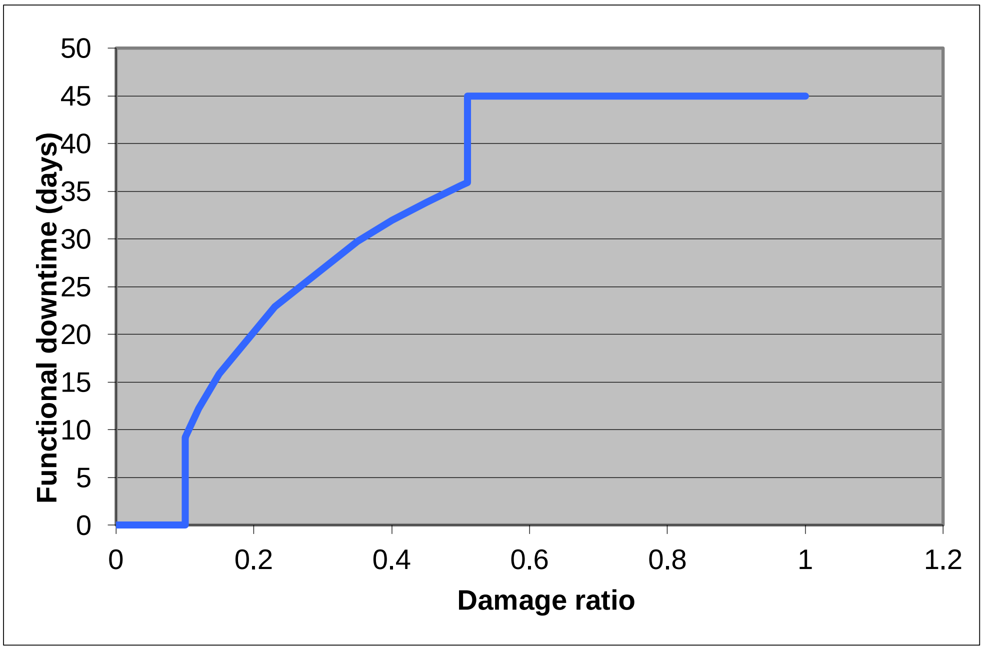

Figure 7: Functional downtime fragility curve for commercial and industrial buildings

3.3 Business disruption—loss of income

Damages or losses are typically categorised as direct or indirect. Indirect losses arise mainly through the second order consequences of disasters, such as the disruption of economic and social activities within and beyond the area of immediate direct physical impact (Smith, 2001; Parker et al., 1985). Indirect consequences also encompass losses due to interruption and damage to transportation, postal and telecommunication networks. Costs of emergency services are a third source of indirect flood costs (Parker et al., 1985).

Economic effects caused by a major disaster could be significant depending on where the boundaries of the analysis are drawn. If a national GDP perspective is taken, the economic effect of the lost trade would normally be small. However, if the analysis is confined to the affected area, the local economic effects can be severe, and potentially as high as the direct costs. On the other hand, there can be a local economic stimulus for some business sectors through demand surge for re-construction and repairs funded by insurers or mayoral relief funds.

Some studies use a fixed ratio between direct and indirect losses to estimate total losses (White, 1964), but this ratio varies dependant on the place and flood characteristics. According to Parker et al. (1987), simple ratios are not appropriate to calculate total indirect losses and indirect losses are unlikely to be greater than direct losses. Investigations they have carried out revealed that in most cases indirect losses were less than 25%, sometimes less than 10%. Only in a few cases indirect losses were greater than 25% due primarily to traffic disruption costs or clean-up costs.

In the post-event surveys conducted as part of the RiskScape project suggests that in 20% of the cases the loss of revenue was indeed higher than the direct costs. Furthermore, in more recent publications (e.g., Penning–Rowsell et al. 2005) the “intangible” effects of flooding are than recognised to be substantial, in particular the human health impacts.

Various methods (regional econometric modelling, input-output models, unit-loss method, etc.) exist to model indirect losses, all with advantages and disadvantages. A simple approach to roughly estimate the loss of income due to business disruption is to use official statistic parameters such as value added. The main advantage of these kind of general approaches is that the method can be applied nationwide, can be easily conducted because the data is publicly available, and can be updated whenever a new statistic is released. Statistics New Zealand carries out an Annual Enterprise Survey[3] (AES) which provides financial information by industry and sector groups.

[3] For more information see Statistics New Zealand: http://www.statistics.govt.nz/methods_and_services/information-releases/annual-enterprise-survey.aspx

The industries covered in the survey contribute approximately 90% of New Zealand's gross domestic product (GDP). AES is an important source of data for GDP as it is used to calculate detailed annual industry National Accounts. Data used in the AES is collected from a number of sources, including:

- Administrative data from Inland Revenue (IR10)
- Central government data from the Treasury's Crown Financial Information System (CFIS)
- Superannuation data from the New Zealand Companies Office (Ministry of Economic Development)
- Local government data from Statistics New Zealand's Local Authority Statistics
- A sample survey of business financial data representing the rest of the population

The statistics include enterprises that meet at least one of the following criteria:

- Has greater than $30,000 annual GST expenses or sales
- Has RMEs greater than two
- Is in a GST-exempt industry (except residential property leasing and rental)
- Is part of a group of enterprises
- Is a new GST registration that is compulsory, special or forced
- Is registered for GST and involved in agriculture or forestry

The Annual Enterprise Survey publishes information concerning the annual income per employee for 17 business divisions (ANZSIC[4]). This data can be used as a rough estimate for the loss of income due to business disruption. The total income encompasses sales of goods and services, interest, dividends and donations, government funding, grants and subsidies and non-operation income.

For the estimation of hazard related business disruption, only the sales of goods and services are relevant. Hence, the total income needs to be reduced by subtracting the non-relevant items.

Based on the assumption that a year has on an average 250 working days, the daily income per employee per business divisions can be ascertained which is then used to estimate the loss of income depending on the flood duration and level of damage.

A business survey carried out in the aftermath of the 2004 Lower Hutt flood enabled the comparison of the actual loss of income with the above approach. The survey provides amongst other things information regarding loss of revenue, the duration of business disruption, flood depths, the total number of employees, type of business and

[4] ANZSIC classification can be found under: http://www.stats.govt.nz/methods_and_services/surveys-and-methods/classifications-and-standards/classification-related-stats-standards/industrial-classification.aspx

clean up time. The average duration of business disruption was 2.9 days, (minimum 0.5 days, maximum 20 days, and standard deviation 3.7). Based on the derived average from the Annual Enterprise Survey and the information from the post-event survey, the loss of income was calculated and compared with the actual number stated in the survey.

The results showed that the annual income per employee of the Annual Enterprise Survey is appropriate as an estimate of loss of income. The calculated loss of income based on this method was only 5% lower than the actual loss. The mean difference was 23%, with a standard deviation 20%.

3.4 Clean-up time and cost

In addition to building fabric and household inventory items, clean-up time and costs are important variables in determining the potential direct damages to residential properties. After the water has receded, clean-up normally begins. This can be a very long process, as apart from any repair that might be necessary, water has to be pumped out, mud and silt has to be removed, cleaning and potentially sterilising has to take place and eventually the building needs to be dried out.

Little information is available from the literature on the time required for clean up. Based on post-event survey information collected after the three flood events, the average clean-up time was 12 days. However, the variance was quite large, with a minimum of 2 days, a maximum of 40 days, and a standard deviation of 12 days. The data showed a clear correlation between the level of building damage (damage ratio) and the clean-up time. The size of the property and how much of it was affected appear also to be relevant factors but unfortunately this information was not collected in the surveys. The estimate of the clean-up time is currently based only on the damage ratio and will be revised when additional information becomes available.

Only very few studies in the literature provide average clean-up costs. Penning-Rowsell et al. (2005) for instance separate clean-up costs based on flooding below and above 0.1 m water depths. For water depth below 0.1m, the estimated clean-up costs are £5,725 (~ $NZ 12,400) and for depths of more than 0.1m, £9,985 (~ $NZ 21,700). An Australian study (City of Ryde, 2009) gives a much lower cost of $AUS 4,000 (~ $NZ 4,900). Due to this large variation, a different approach has been incorporated within RiskScape based on the estimated clean-up time and an hourly labour rate for residential, commercial and industrial buildings of $20, $80, $45 per hour respectively.

4. People-related impacts

4.1 Social vulnerability / vulnerability indexes

Assessing the impacts of natural hazards involves much more that just assessing the direct costs of damage to exposed buildings, their contents or to infrastructure. How people and communities are affected by disasters is particularly important. How vulnerable someone is, is determined by various factors such as by personal attributes, community support, access to resources and governmental management, etc. Hence, it is important to address this social vulnerability.

Normally, indicators are used to measure social characteristics to provide decision-makers with a useful tool. There are a number of ways reported in the literature that this could be achieved. The most readily accessible in a New Zealand context is the national Deprivation Index developed by the Department of Public Health, Wellington School of Medicine and Health Sciences (Salmond and Crampton, 2006). This is a measure of socio-economic deprivation at census meshblock level that combines nine variables from the 2006 census, reflecting eight dimensions of deprivation (Table 4).

The deprivation index is a reflection of how well a group of households can achieve positive outcomes in areas such as health, income, education and employment. The index scales deprivation in two forms: 1) the index, with a mean scaled to 1000 index points and a standard deviation of 100 index points, and 2) derived from this a scale of 1 to 10, where a value of 10 indicates that the meshblock is in the most deprived 10 percent of areas in New Zealand.

Table 4 Deprivation index variables

Dimension of deprivation	Variable description (in order of decreasing weight)
Income:	People aged 18–59 receiving a means tested benefit.
Employment:	People aged 18–59 unemployed.
Income:	People living in equivalised[5] households with income below an income threshold.
Communication:	People with no access to a telephone.
Transport:	People with no access to a car.
Support:	People aged < 60 living in a single parent family.
Qualifications:	People aged 18–59 without any qualifications.
Owned home:	People not living in own home.
Living space:	People living in equivalised1 households below a bedroom occupancy threshold.

The index was derived primarily to assist decision making in the health sector. However, many of the parameters are of direct relevance for assessing social vulnerability to natural hazards with the main advantage being is that it is readily available. The deprivation index is not used in any of the flood related fragility functions but provides additional information on social vulnerability.

4.2 Assessing human susceptibility, injury and fatality rates

There are a number of methodologies derived for assessing injury and fatalities due to flood risk. Most have been derived from significant flood events including dam break events, typically in Europe and the US. Ramsbottom et al. (2003) provides a summary of methodologies for assessing the impact of flood events on people and property. Some methods are based exclusively on the water depth (CUR, 1990), others only on the flow velocity (USACE, 1993). The Dutch so called "Standaardmethode" (Kok et al., 2005) includes the water depth and the rate of the rising water. Asselman & Jonkman (2003) propose all three parameters, whereby the flow velocity an indication of a possible building collapse is. Tapsell et al. (2009) points out that the mortality depends not only on the type of flood event but also on various other factors like

[5] Equivalisation: methods used to control for household composition.

people's behaviour, their vulnerability, property characteristics, flood warning, etc. Based on data on flood events from 25 locations across six European countries, Tapsell et. al., (2009) developed a new methodology, which combines hazard, exposure and mitigation to estimate the risk to people's life.

Given the various factors that affect the cause of death or injury, the task of modelling this is extremely complex. Hence, a two step approach has been developed. Firstly, Tapsell et al's (2009) risk to life model has been adopted to estimate human susceptibility to potential flood-related harm. This is a qualitative approach of estimating what the risk of getting injured or killed is. The number of injuries and fatalities are then calculated as a function of the risk to life, which in turn is estimated based on the flood characteristics (depth and velocity), characteristics of the area flooding and nature of the population. As the risk to life approach was seen as complementary to the quantitative calculation of injuries and casualties, it was decided to use this as a separate output for RiskScape.

Priest et al. (2007) describe the risk to life model as a new semi-qualitative threshold model that combines hazard and exposure thresholds and mitigating factors. It has the flexibility to be used at a range of scales.

4.3 Human susceptibility

The concept of the "risk to life" model (Tapsell et al, 2009; Priest et al., 2007) was used for RiskScape but input parameters were amended due to differences in data availability and to adjust the method to New Zealand conditions. The following parameters were included:

- Flood depth and *vd* (velocity*depth product). Speed of onset was not implemented as it is currently not available
- Vulnerability (escape story, damage state of building, use of building)
- Mitigation (warning, evacuation; defined by the user)

Output from this risk to life model is a low, medium, high and extreme risk depending on different combinations and weightings of the input parameters[6]. The areas not affected or outside the flood plain are naturally in low risk category.

[6] For detailed description of the Risk to Life Model see Tapsell et al (2009) and Priest et al. (2007)

Table 5: Risk to life categories

Risk to life
Low
medium
High
Extreme

There are other factors that can influence the number of flood casualties such as population density or population characteristics (e.g. age, prior health, disability, presence of tourists). Some of this information is difficult to obtain or is dependant on people's behaviour (e.g. driving through floodwaters) and unpredictable.

Based on an analysis of data from various European flood events, Tapsell et al. (2009) also recommend that people vulnerability should be given less prominence and the effects of warnings and type of buildings more prominence. Thus, it was decided to not include people vulnerability (i.e deprivation index) into the injury and fatality method.

To account for the variance and uncertainty in flood casualty estimation, a probabilistic instead of an empirical approach was chosen.

4.4 Injuries and fatalities

While the devastation to properties is usually obvious following a flood event, the impacts on people can be far greater than the monetary damages and sometimes also more subtle.

Health effects are usually categorised into different groups (Tunstall et al., 2006; Fewtrell & Kay, 2008), namely:

- Mortality or injuries experienced during or immediately after the flooding (physical health effects)
- Physical health effects experienced in the weeks and months following flooding
- Psychological or mental health effects

There are few studies that provide accurate information about total mortality and injury rates for floods. Legome et al. (1995) report that most of the flood related deaths are due to drowning and between 40% and 50% of the drownings are car related where people drive along flooded roads or across flood bridges. However, deaths related to flood-induced illnesses tend not to be reported and incorporated in flood-related mortality statistics. Tunstall et al. (2006) interviewed 983 affected people in the aftermath of a major flood in the UK. The results showed that 54% of those people suffered immediate physical health effects, 33%, physical health effects in the weeks after the event, and 71% reported to have psychological illnesses. Dominant effects were shocks and colds for the first category, gastro or respiratory illnesses and anxiety, stress and sleeping problems for the second and third category. However, only 23% of all those people consulted a doctor. The study also revealed that various social and other factors might have an influence on people's health conditions and effects. Azeredo (2001) reports that natural, environmental, and human behavioural factors play a role whether flooding and flash floods result in death. McClelland and Bowles (2002) suggest that there are nearly 100 quantitative or categorical variables which can be considered to affect the number of flood fatalities. Jonkman et al. (2008) provides a good overview of existing loss of life approaches.

To ascertain typical casualty numbers in New Zealand, flood events, historic information was analysed. As part of RiskScape, a database on historic weather related events has been created. This database enabled the number of casualties to be ascertained for all documented floods since 1840. In most events, the number of fatalities is low, with only a few events in the 19th century with up to 100 casualties. If only data post 1900 is considered, the average mortality per flood is 1.4 (median 1, standard deviation 1.9). Two events stand out, an event in 1938 where 20 people died in a construction camp at the Kopuawhara Stream, and the event in 2008 where a teacher and six students died in the Mangatepopo River. The small number of casualties can probably be attributed to the often low population density and remoteness of a lot of rivers, as well as regular and frequent weather warnings and a good general awareness of the risk of rapidly rising rivers. Unfortunately, the historic database does not hold information on injuries. Other studies (Zhai et al. 2006; Legome et al., 1995) suggest a ratio between fatalities and injuries of 1:10 but it is assumed that this does not include the 80% who do not seek medical attention.

The RiskScape casualty method takes the output from the risk to life model and calculates the number of injuries and casualties based on the estimated risk.

The number of injuries and casualties are combined in the impact category "Human Losses". The following categories exist:

- Category 0: No or light injury
- Category 1: Moderate injury
- Category 2: Serious injury
- Category 3: Critical injury
- Category 4: Dead

Each risk category was assigned a certain probability, which defines how many people out of the total number in that category may experience some form of injury. The highest risk category has naturally the greatest percentage of people getting injured or killed. However, there is even a chance that people who live outside the flooded area—are in the low risk group—might expose themselves by making the wrong decision, i.e. walk down to the river to watch the flood. Hence, 0.5% of the people in the low risk category are likely to be injured or killed (Table 3). The remaining 99.5% will go into Cat 0 (no or light injuries). In the extreme risk category 10% of the people are likely of being injured or killed.

As mentioned earlier, about 80% the people who have minor injuries or illnesses normally do not seek medical treatment. These people fall into category 1, i.e. a moderate injury. To account for this number, a weighting was incorporated. This ensures that 80% of the people that will sustain an injury (category 1–4) fall into category 1 (moderate injuries). The residual percentage will be semi-randomly distributed across the three remaining casualty categories (2, 3 and 4). A further weighting ensures that more people are in category 2 than in 3 and 4, etc.

However, the weighting only applies if the total number of people who are likely to experience an injury is greater than 10 people, otherwise no weighting will be done and scaled random numbers are generated for classes 1–4.

Table 6: Injury and mortality probability based on the risk to life

Risk to life	Percentage of total that may experience some form of injury (catagories 1 to 4)	Percentage of total that sustain no or light injuries cat. 0
Low	0.50%	99.5%
Medium	1%	99.0%
High	5%	95.0%
Extreme	10%	90.0%

5. Vehicle damage

Vehicles are frequently affected by flooding and a separate fragility curve was developed for motor vehicles.

Unless there is significant flow velocity it is assumed that damage will be experienced as soon as the water is above the level of the base of the doors (and can enter the interior) which is roughly at a height of 0.3m. Laboratory tests in Germany (Pflügner, 2001) revealed that once the water has entered the car, a loss of about 25% occurs due to damage to seats, floor coverings or other interior fixtures (Figure 8).

The next step of the fragility curve occurs at 0.6–0.8m when the electronic circuits of the cars are affected. Beyond this height the damage increases continuously up to 1.5m where the entire car is filled with water. It can be expected that at this stage that 100% damage occurs with insurance write-off of the car. Where a vehicle becomes buoyant or gets washed away due to moving water, 100% damage is assumed. For an average New Zealand car, critical *vd* (velocity * depth product) values were calculated and integrated into the fragility function shown in Figure 8. Should vd exceed the calculated threshold, a total damage is assumed.

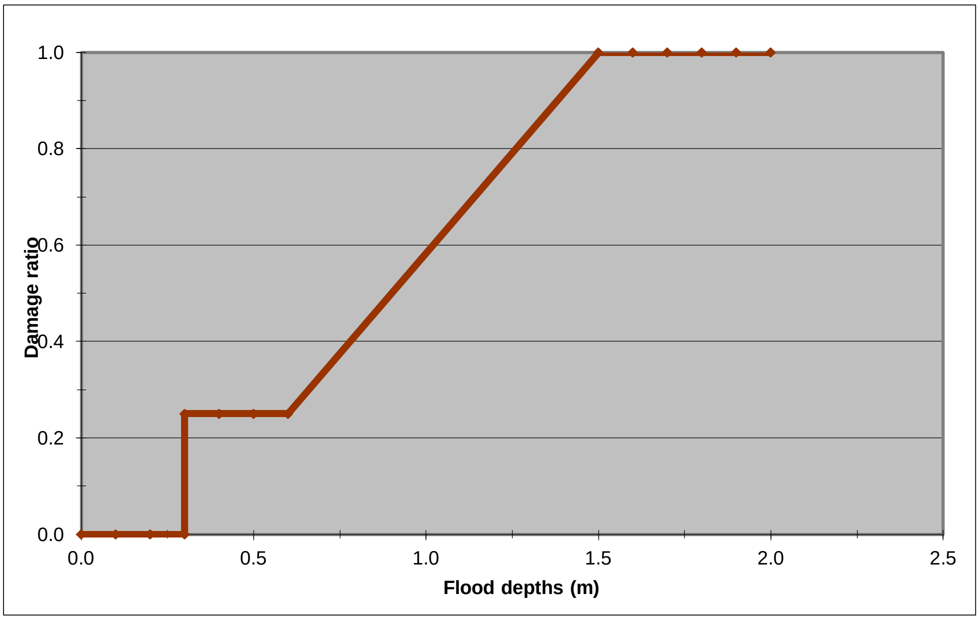

Figure 8: Vehicle fragility curve

6. Infrastructure

6.1 Introduction

Within RiskScape at present the potential to assess direct damage to lifeline infrastructure is limited to the road network and the water / wastewater system.

6.2 Road network

The road network from Land Information New Zealand (LINZ) used within RiskScape includes only linear features such as roads and highways but not elements like parking areas. Road networks are vital infrastructure lifelines both during and after flood events. Flooding can cause significant disruption to transportation, leading to access difficulties for emergency services during events, significant repair costs, and disruption to road users and the community during and in the aftermath of such events.

Direct damage to roads and other traffic areas from flooding is normally relatively minor compared to other categories such as buildings and contents. The American Lifelines Alliance (2005) list the following damages, ranging from ditch scour to complete collapse of a length of road bed or embankment:

- Saturation and collapse of inundated road beds
- Loss of paved surfaces through flotation or delamination
- Washout of unpaved roadbeds
- Erosion and scour of drainage ditches, sometimes to the extent of undermining shoulders and roadbeds
- Damage to or loss of underdrain and cross-drainage pipes
- Blockage of drainage ditches and underdrains by debris, exacerbating erosion and scour
- Undermining of shoulders when ditch capacity is exceeded
- Washout of approaches to waterway crossings
- Deposition of sediments on roadbeds

Most of the structural damages are due to high flow velocities or wave activity. Typical damage is in the form of erosion of the road surface, erosion of shoulders and embankments. Depending on the shoulder / embankment material and geometry, erosion generally commences at the toe, slope, or crest of the road structure before affecting the actual road surface. To assess the potential for structural damage requires information on the geometry and characteristics of the embankment or road shoulder. Where flood inundation modelling has been conducted, information on the shape and steepness of the embankment is typically available from the digital elevation model used within the model. Hence both depth and velocity information is available over the road system. Both the steepness of any embankment and flow velocity are key factors in determining potential damage. The third important factor is the covering of the shoulder / embankment. Apart from conducting a site specific assessment, information on the shoulder / embankment covering characteristics is not available. Rather within RiskScape it has been assumed that this is grass. Very little quantitative information can be found in the literature on structural damage to roads from flooding. Given the dominance of erosion and scouring induced damages, a fragility function has been developed using critical erosion velocity thresholds dependent on the local topography.

Aside from potential structural damage clean-up costs will almost always occur on a road that has been subjected to flooding. The only available data was from a German study (Reese, 2003). Based on this a clean-up cost of NZ$12 per m^2 of flooded road is assumed within RiskScape.

In addition to potential structural damage and clean-up costs, the economic impacts of road / traffic disruption can be significant. Detours for instance can add significantly to the costs of a business (for example, increased travel time costs and fuel, bus companies having to provide alternative transport to passengers who miss connections). At present assessing such economic costs is not incorporated within RiskScape but will be addressed in the near future.

6.3 Water transport and distribution systems

Disruption to water and wastewater systems during natural hazard events can have a major impact on community recovery in the aftermath of such events. Water infrastructure normally comprises a water-supply, wastewater and stormwater network, consisting of various elements such as pipes, pump stations, manholes, valves, etc. Only certain structures are prone to flood damage as most elements such as manholes are not susceptible. As with building damage the most important factors are water depth, water velocity, inundation duration as well as the amount of debris and sediment carried by the flood water.

Most urban drainage systems are designed to cope with a flood event of a certain magnitude. Recent extreme weather events have shown that these systems are often the 'achilles heel' of urban flood management. In some cases wastewater systems have functioned in reverse resulting in water entering housing through the wastewater pipes.

High rainfall events are also a problem for the water-supply network primarily though inundation at pumping stations, valve chambers, treatment plants and similar structures, rather than issues associated with water supply pipelines. Pump stations are likely to be the most vulnerable components of the water system with both damage to the equipment and building possible. However, the potential impacts are highly variable depending on the characteristics of each individual pump station, such as the vertical location of electrical or mechanical equipment, control units and telemetry.

There is very little fragility data on water transportation networks available in the international literature. The main source is the HAZUS technical manual (FEMA, 2003) which provides a comprehensive set of flood fragility functions for various utility elements including the water network. However, the applicability of these curves to New Zealand water transportation system was questionable and so it was decided to develop new fragility functions.

The RiskScape fragility functions were developed in collaboration with Engineers from Christchurch City Council. This provided estimates of possible damages dependent on water depth within the station. The potential for damage and restoration times are primarily a function of the fragility of:

1. Electrical equipment

2. Mechanical equipment

3. Building damage

In many situations, the level of damage is also dependant on a management decision to shut the facility down. However, irrespective of facility shut down, mechanical and electrical equipment as well as the control system could potentially sustain damage, ranging from 5% to 100%, if they are inundated.

While HAZUS has only one fragility function for a generic pump station, it was apparent that stormwater, water-supply and sewage pump stations show different damage characteristics. Hence, separate fragility functions based on inundation for each of the water networks for treatment plants, pump stations (above and below grade), and pipelines were developed (excluding building damage). Figure 4 shows the fragility function for all pump stations.

Pump stations can be above or below grade (ground level), with inundation impacts very different for these two situations. For above grade facilities, the damage will gradually increase to a maximum as the water depth increases to a defined level. For below-grade facilities (e.g. sewage pumps) there will be no damage until the water elevation rises above the ground floor slab elevation. Once that elevation has been exceeded, maximum damage would be reached.

No new building fragility functions were developed as it was assumed that the commercial or industrial building fragility functions could also be applied to pump station structures.

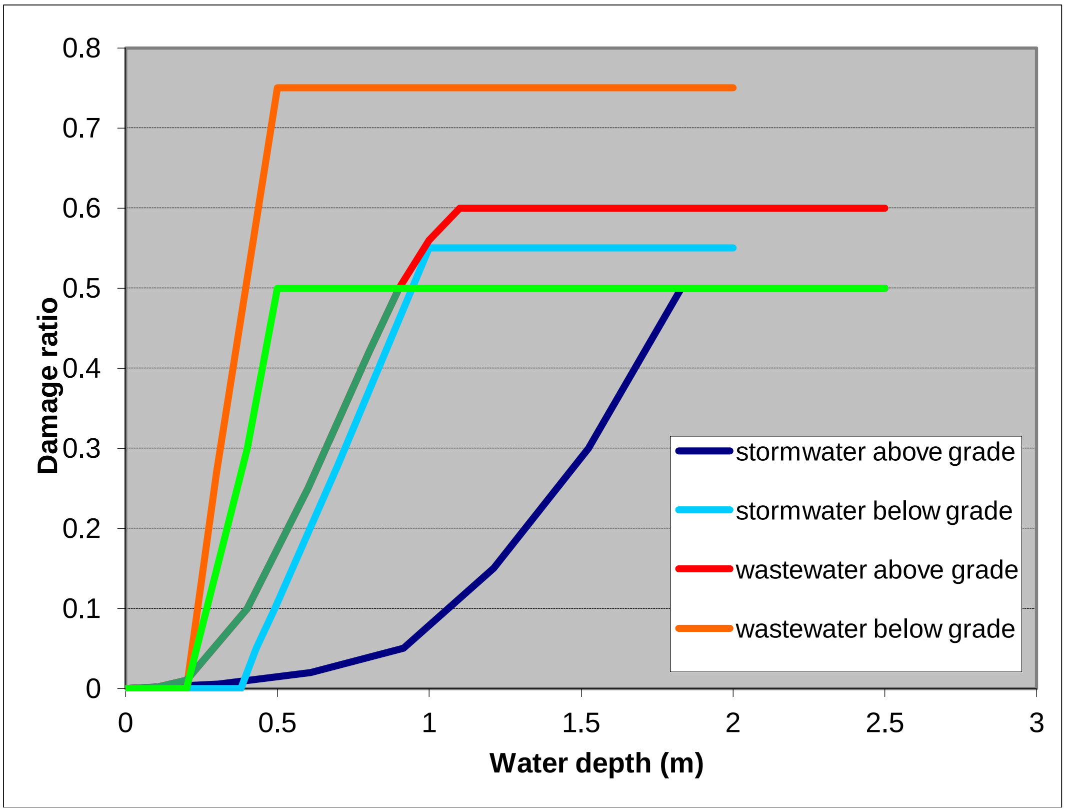

Figure 9: Flood fragility functions for water transportation pump stations

Water pipelines range in size from just a few centimetres to over several meters in diameter and can supply water to communities and industries over both short and long distances, or to transport stormwater or wastewater for treatment or disposal. Water pipelines are normally classified into transmission, sub-transmission and distribution pipelines and common materials include concrete, metallic, plastic and fibreglass.

Most of the pipeline network in New Zealand is buried at varying depth below the ground surface. In Christchurch for instance the majority of the pipes are between 1and 3m beneath the surface. Structural damage to the buried network is unlikely unless heavy erosion or scouring occurs. Hence, only clean-up costs would occur.

Estimates for pipe clean-up costs were provided by the engineers from Christchurch City Council. These costs are dependant on the diameter of the pipe and the amount of sediment.

Erosion occurs when soil materials are displaced by the action of water currents. However, erosion has far more variable factors, some of which cannot be determined with any degree of certainty. Hence, assumptions were made based on the personal experience, pipes are typically between a quarter to half full of sediment, with an average of 3/8. Only stormwater and sewage pipelines are likely to be affected by sediment as sediment can normally only enter the water-supply network through wells or reservoirs.

Streams and open stormwater channels also play an important role in stormwater management. In New Zealand some of the urban stormwater pipes discharge into streams. These channels and streams also collect stormwater from private property and provide drainage for public areas, such as roads and parks. There are normally three different stormwater drain types, lined channels, earth channels and utility waterways. In case of a flood erosion and debris will be the primary impacts. As for pipelines, only clean-up costs were considered at this stage, varying whether drains have truck access or not. The costs only consider removal of "uncontaminated" sediment to a landfill on the city perimeter. The costs for removal of contaminated sediment would be five times higher.

7. Limitations, uncertainties and future work

The incorporation of fragility functions within RiskScape is considered to be a first step in deriving hazard-damage functions.

In terms of flood-related damage, the primary focus has been on flood depths and flow velocity. However, other factors cause, or contribute to the level of damage that can result from such events, such as flood duration, contamination and the amount of debris carried by the water. Incorporating flood duration considerations, with information on the duration easily obtained from the flood model, is relatively straightforward However, developing methodologies to incorporate debris and contaminant effects are much more difficult to quantify and develop.

Whilst some verification of the fragility curves has been conducted, verification data is sparse. Hence, all fragility functions require further verification against actual flood events and are subject to change and this will be carried out as flood events occur and further field information can be collated. Other work planned within RiskScape includes:

- Incorporating flood duration considerations
- Development of fragility curves for other infrastructure elements such as bridges, where there is little information in the international literature
- Include other network data such as telecommunication or power
- Incorporation of indirect and intangible costs such as disruption,
- Move to a probabilistic approach rather than providing mean damages
- Complete and extent set of fragility functions through further post impact surveys

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