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Calibration and validation of FLFA$_{\text{rs}}$ – a new flood loss function for Australian residential structures

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Abstract. Rapid urbanisation, climate change and unsustainable developments are increasing the risk of floods. Flood is a frequent natural hazard that has significant financial consequences for Australia. The emergency response system in Australia is very successful and has saved many lives over the years. However, the preparedness for natural disaster impacts in terms of loss reduction and damage mitigation has been less successful.

In this paper, a newly derived flood loss function for Australian residential structures (FLFA$_{\text{rs}}$) has been presented and calibrated by using historic data collected from an extreme event in Queensland, Australia, that occurred in 2013. Afterwards, the performance of the method developed in this work (contrasted to one Australian model and one model from USA) has been compared with the observed damage data collected from a 2012 flood event in Maranoa, Queensland. Based on this analysis, validation of the selected methodologies has been performed in terms of Australian geographical conditions.

Results obtained from the new empirically based function (FLFA$_{\text{rs}}$) and the other models indicate that it is apparent that the precision of flood damage models is strongly dependent on selected stage damage curves, and flood damage estimation without model calibration might result in inaccurate predictions of losses. Therefore, it is very important to be aware of the associated uncertainties in flood risk assessment, especially if models have not been calibrated with real damage data.

1 Introduction

Studies have shown that compared to other types of natural hazards, floods are a considerable threat to a nation's economy, the built environment, and people (André et al., 2013; Kourgialas and Karatzas, 2012; Llasat et al., 2014; UNISDR, 2009). Furthermore, in recent decades, the flood risk due to climate change and the growth in value and vulnerability of exposed properties has been increasing exponentially (Elmer et al., 2012; Kundzewicz et al., 2005), which subsequently raises the significance of flood risk management. Flood damage assessment in order to mitigate the probability of expected losses is an important part of the risk management process (André et al., 2013; Elmer et al., 2010; Kaplan and Garrick, 1981), and the results will provide decision-makers, emergency management organisations, and insurance and reinsurance companies with a tool for planning better risk mitigation strategies to cope with future disasters (Emanuelsson et al., 2014; Merz et al., 2010).

In general, there is no common agreement among terms such as damage, loss and impact, but flood damage can either be categorised as direct or indirect. The direct category occurs due to physical contact between the floodwater and the inundated objects, and the indirect category is based on the effects of direct damage on a wider scale of space and time (Meyer et al., 2013; Molinari et al., 2014a; Thieken et al., 2005). Both categories can be evaluated as marketable (tangible) or non-marketable (intangible) values (André et al., 2013; Kreibich et al., 2010). The focus of this study is on direct, tangible damages to residential building structures due to a short duration of riverine (low-velocity) inundation.

Direct tangible damages of floods before they occur can be estimated by an averaging method such as the rapid appraisal method (RAM) or by function approaches such as depth–damage curves (Molinari, 2011). The RAM is a simplified method for flood damage estimation in the absence of data required for using depth–damage curves (Sturgess and Associates, 2000). This method considers mean unit values of damage for all buildings in the inundated area. Although RAM is useful for early assessment of the magnitude of damage, the results are considerably inaccurate (Barton et al., 2003).

The function approach is a common and internationally accepted methodology for estimating the relative or absolute value of losses via a causal relationship among the magnitude of the hazard (e.g. the depth of water), the level of vulnerability (e.g. the building type), and the expected damages (Dewals et al., 2008; Jongman et al., 2012; Kreibich and Thieken, 2008; Molinari et al., 2014b; Smith, 1994; Thieken et al., 2006). This approach varies from traditional functions, i.e. functions which are solely based on the type or use of an element at risk and the water depth, to multi-parameter probabilistic loss models (Merz et al., 2013; Schröter et al., 2014). It is worth noting that these functions are strongly restricted to the area of origin, and transferred functions to a new geographical condition do not establish an appropriate relationship between the magnitude of the flood and the value of losses unless they have been adapted and calibrated with the conditions of the new region of study (Cammerer et al., 2013; Molinari et al., 2014b). Therefore, one important step in model development is model validation. In general, obtaining a reliable estimation of flood consequences by using a depth–damage function with an accurate and calibrated shape is considered more necessary than precision in collecting hydraulic inputs and flood characteristics (Apel et al., 2009).

Due to a lack of historic data, few studies have been conducted to explore the validation of well-known overseas methodologies in other flood-prone regions (Cammerer et al., 2013), and also for calibrating local Australian methodologies with empirical data. This study aims to present a new flood loss model (FLFA$_{rs}$) for the Australian geographical conditions by using historic data collected from an extreme event that occurred in the Bundaberg region of Queensland, Australia, in 2013. In addition, the accuracy of the results obtained from the newly derived model and two existing models was compared using historic data collected from the Maranoa flood event (2012).

2 Background

Stage damage curves have been grouped into two main classifications: empirical and synthetic curves. Empirical curves build on surveyed damage data. They estimate the actual damage as they take into account the effect of mitigation measures. Also, variability within one category of building and water depth is reflected by the surveyed damage data (Kreibich et al., 2005; Merz et al., 2010, 2004). However, Smith (1994) discussed that by moving in time and space, the warning time, level of preparedness in society, and the characteristics of a building could vary considerably. Therefore, gathering data from one actual flood event and using it as a guide for future events in a new area of study, or even in the area of origin, requires a complicated process of extrapolation (Gissing and Blong, 2004; Smith, 1994). In other words, extrapolation of empirical damage curves to different regions is difficult due to differences in the level of precaution and differences in building characteristics (Barton et al., 2003). As a solution, synthetic curves based on a valuation survey have been created for different types of buildings. Valuation surveys refer to the value and elevation of all components that are located above the basement. This means that, by using valuation surveys, an average distribution of building fabrics in the height of the structures would be extracted (Barton et al., 2003). Afterwards, the magnitude of potential damage for different water levels via “what-if” questions is estimated based on their average distribution in the height of the structure and the level of vulnerability of each component (Gissing and Blong, 2004; Merz et al., 2010).

Based on the valuation survey, several synthetic local damage curves have been prepared for Queensland, Victoria, and New South Wales. Most of the synthetic methodologies prepared for Australia are not calibrated with empirical loss data, and few studies have been done on result comparison and uncertainty estimation. As mentioned earlier, these curves will estimate the potential damage based on “what-if” questions. Potential losses are the maximum possible value of losses without considering any mitigation measures (Bureau of Transport Economics, 2001; Molinari, 2011; Molinari et al., 2013). Usually, potential damage is the greatest value of losses, and its magnitude is more than the actual damage (Molinari, 2011; Molinari et al., 2013). To address this issue and increase the level of accuracy, FLFA$_{rs}$ has been calibrated with an empirical database.

Functional approaches can also be categorised as absolute and relative types. Absolute functions express the magnitude of damages in monetary values, while relative types estimate the dimension of losses as a ratio of the total value, i.e. replacement value or depreciated value (Kreibich et al., 2010). Almost all of the approaches available in Australia are absolute. These types of curves, compared to relative damage curves, are less flexible for moving in the spatial scale or time since they are dependent on changes in market values (Merz et al., 2010). For instance, the RAM report (Sturgess and Associates, 2000) claims that the magnitude of damage estimated by ANUFLOOD curves (Gissing and Blong, 2004; Smith, 1994) should be increased by 60 %. The reason for this is related to the fact that these curves were prepared based on data from a 1986 flood in Sydney, and also due to changes in the value of the dollar compared to today's value. Hence, their results are no longer reliable. Also, some updated absolute approaches such as that used in Nerang, Queensland, prepared by Gold Coast City Council (Barton et al., 2003), are restricted to the area of origin. In transferring such curves to a new study area of Australia, the differences in the replacement value of the exposed items or repair costs of assets will decrease the reliability of the results. With regard to moving in space or time, and compared to the available methodologies, the authors have tried to increase the level of flexibility of the newly derived model.

A general lack of data regarding the logic behind existing state reports and their methods is observed by end users and researchers in Australia. To be more precise, a number of methods have been identified, such as the Geoscience Australia model (Geoscience Australia, 2012), and the NSW government curves (Office of Environment and Heritage; New South Wales Government, 2007), but no specific detailed literature has been published about them. However, the new method developed in this research (FLFA$_{\mathrm{rs}}$), in addition to its flexibility and transferability in time and space, is simple enough to understand and generalise to other types of buildings and vulnerability classes.

Although the detailed valuation survey proposed by Smith (1994) seems a little complicated and time-consuming even for data gathered from one type of building (Merz et al., 2010), the new model for evaluating the assembly items and tracking the vertical parameters by considering more general categories has attempted to simplify the process as much as possible.

3 The newly derived loss model (FLFA$_{\mathrm{rs}}$)

The residential synthetic stage damage curves can be developed by employing the following steps (Bureau of Transport Economics, 2001):

- Based on the characteristics of buildings in the area of study (e.g. material and size), some representative classes should be selected.
- For each selected class, an average distribution of the assembly items in the height of the buildings should be extracted.
- Finally, based on the average value of the flooded items relative to the total value of the building and the degree of fragility of each item, stage damage curves for different depths of water can be constructed.

As mentioned above, a disadvantage of the synthetic methodology may be attributed to the significant effort in gathering data and details for the valuation survey, in addition to ignoring the effect of early warning and damage mitigating actions (Merz et al., 2010). For resolving the first issue, a more general and simplified method has been followed by this study. For resolving the second issue, the results of this study have been calibrated with the relevant empirical data set.

To be more specific, four common vulnerability classes and building types for the selected area of study in Australia have been considered:

- one-storey buildings with masonry walls and slab-on-ground construction;
- two-storey buildings with masonry walls and slab-on-ground construction;
- one-storey buildings with timber walls and slab-on-ground construction; and
- two-storey buildings with timber walls and slab-on-ground construction.

This selection has been made based on the data collected from the national exposure information system of Australia (Dunford et al., 2014). This data set shows that 74 % of residential buildings in our areas of study are made with masonry and timber walls. Moreover, 99 % of these buildings are one and two storeys high.

Also, assembly items of the buildings based on the proposal of the HAZUS technical manual (FEMA, 2012) have been categorised into five general groups:

- foundation and below first floor, which includes site work, footings, walls, slab, piles, and items that are located below the first floor of the structure;
- structure framing, which includes all of the main load carrying members below the roof and above the foundation;
- roof covering and roof framing;
- exterior walls, which includes wall coverings, windows, exterior doors and insulation; and
- interiors, which includes interior walls and floor framing, drywall, paint, interior trims, floor coverings, cabinets, and mechanical and electrical facilities.

The general methodology is to describe the damage for each stage of water using a general function. Based on the recommendations of the HAZUS technical manual (FEMA, 2012) and the knowledge of experts, different sub-assembly groups start damaging in different stages of flood. In other words, the first non-zero percentage of damage for each group will occur after a specific level of total damage of the building and subsequently to different water depths. This fact shows that the slope of the damage curves could vary based on an exponential equation (Cammerer et al., 2013; Elmer et al., 2010; Kreibich and Thieken, 2008). On the other hand, as described in detail by the HAZUS technical manual and the Australian construction cost guide (Rawlinsons, 2014), the replacement value of interiors and exterior walls, which start damaging from the first stage of water, are about 70 % of the total replacement value of the building. This means that for the first few metres of flood, the rate of damage due to storing the utility facilities is greater than the remaining stages. Therefore, the power of the following exponential Eq. (1) can control the rate of change in the percentage of damage compared to the increment of water depth. The accurate value of r for each vulnerability class will be extracted based on empirical data, but we can say that in general, a higher value for r means faster inclines at lower depths, which results in damage occurring more quickly in the first few metres of each floor. The formula for a one-storey building could be considered as

$$d_h = \left(\frac{h}{H}\right)^r \times D_{\mathrm{max}}, \tag{1}$$

where d_h is the percentage of damage corresponding to the depth of water, h the depth of water, H the maximum height of the building, D_{max} the maximum percentage of damage corresponding to the maximum height of the building, and r is the rate control.

In typical residential buildings (urban buildings that are generally uniform from the second floor) with more than one storey, the first floor of the building contributes more damage than the other stories because most utilities and electrical equipment are stored there, as well as in the basement. Therefore, this formula enables the user to define the level of damage that would occur between the first floor elevation and the top of the rafters of the first floor, and how much typical damage will be distributed among the other storeys. The generalised formula for damage estimation in each storey of a building based on the maximum percentage of damage and the appropriate value for rate control r can be expressed as

$$d_{hi} = \left(\frac{h_i}{H_i}\right)^{r_i} \times D_{\mathrm{max}i}, \tag{2}$$

where d_{hi} is the percentage of damage for the ith floor corresponding to the depth of water above the ith floor, h_i the depth of water above the ith floor, H_i the height of the ith floor, $D_{\mathrm{max}i}$ the maximum percentage of damage for the ith floor, and r_i is the rate control for the ith floor.

Overall, for this concept, the authors have tried to create a simple and flexible curve with regards to the variability in the number of storeys, height of storeys, and the distribution of components through the height of the building. Therefore, users can manipulate and calibrate this model easily based on the characteristics and types of buildings for other areas of study.

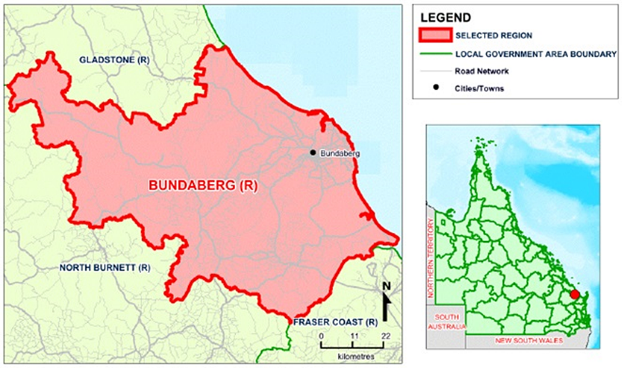

Figure 1. Map of Bundaberg Regional Council (Queensland Government, 2011a).

4 Study areas and official loss data

4.1 Study areas and flood events

For this study, two areas have been selected. The first study area is Bundaberg city in Queensland, Australia. Location of this city, as illustrated in Fig. 1, is part of the Bundaberg region located north of the state's capital, Brisbane. The economy of the Bundaberg region is mainly dependent on the agricultural sectors, service sectors, and the tourism industry (Queensland Government, 2011a). In recent years, this city has experienced some extreme flood events because it is located in the vicinity of the Burnett River waterway. The Bundaberg ground elevation and the Burnett River catchment are illustrated in Figs. 2 and 3. The most recent flood responses from Bundaberg Regional Council date back to the floods in November 2010, January 2013, February 2013, and February 2015.

The empirical data used for calibrating $\mathrm{FLFA_{rs}}$ were collected after the January 2013 Bundaberg flood event. This flood event that occurred from 21 to 29 January 2013 was a result of Tropical Cyclone Oswald, and the associated rainfall and flooding had a catastrophic effect on Queensland, with it being considered as the worst flood experienced in Bundaberg's recorded history. The height of the floodwaters in Bundaberg city from Burnett River reached 9.53 m at its peak, and over 2000 properties were affected (Queensland Government, 2013). The propagation of the water depth is illustrated in Fig. 4. During this flood event in the Bundaberg region, 200 businesses were inundated and over 2000 residents and 70 hospital patients were evacuated. Furthermore, the natural gas and power supplies were disrupted, agricultural and marine environments were impacted, and usage of coal and insurance claims dramatically increased (Queensland Government, 2013). In addition to this significant damage level, closures of the Bundaberg port, railways and roads had a considerable effect on the economy of this region. According to comments from the communications team of

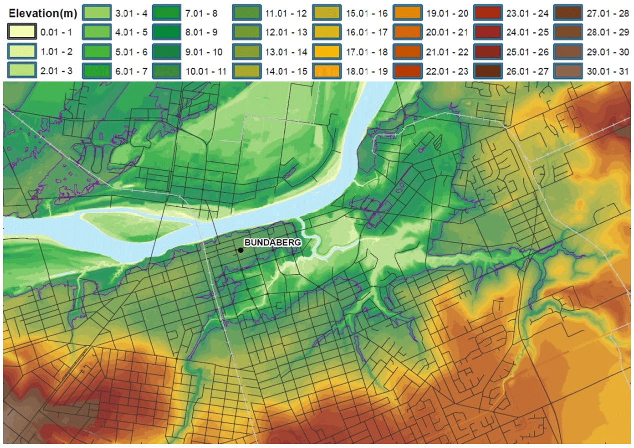

Figure 2. Bundaberg ground elevation (Bundaberg Regional Council, 2013a).

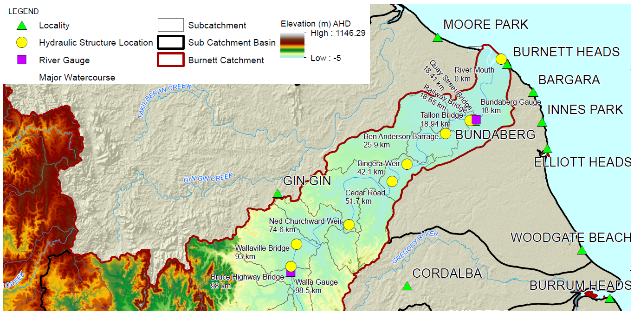

Figure 3. Burnett River catchment map (Bundaberg Regional Council, 2013b).

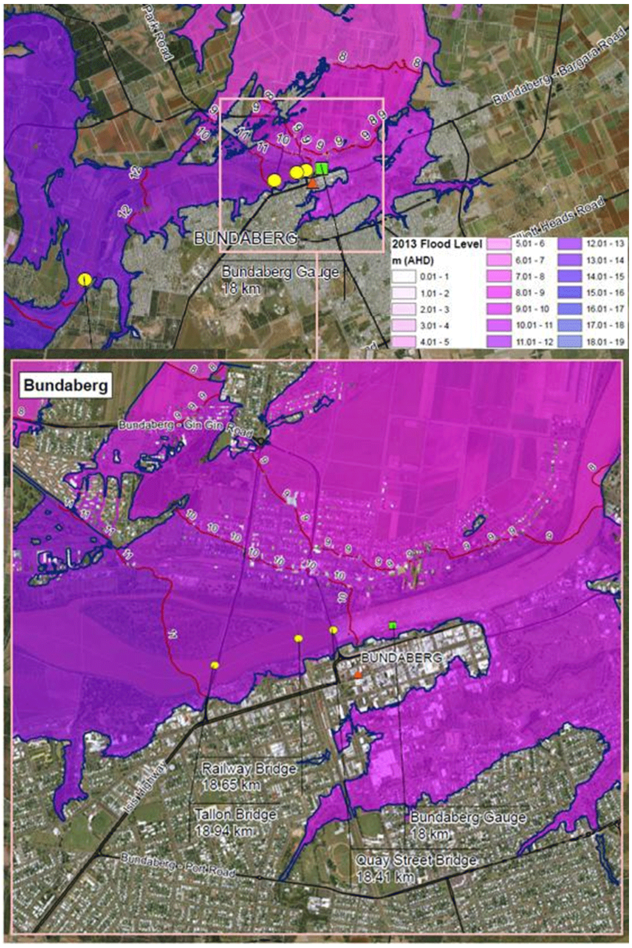

Figure 4. Inundation map of 2013 flood (Bundaberg Regional Council, 2013c).

the Queensland Reconstruction Authority, Bundaberg Regional Council estimated that the public infrastructure damage from the natural disaster events of 2013 was approximately AUD 103 million.

Furthermore, for validating the applied damage models, empirical data collected from 2012 flood event in the city of Roma, located in the Maranoa region in Queensland, have been utilised. This town, as illustrated in Figs. 5 and 6, is situated on Bungil Creek, a tributary of the Condamine River. The top five industry subdivisions of employment for workers in the Maranoa Regional Council are agriculture, public administration, education, oil and gas extraction, and retail stores (Queensland Government, 2011b). According to comments from the communications team of the Queensland Reconstruction Authority, in the last few years, the Maranoa Regional Council has had to respond to the following disaster events:

- heavy rainfall and flooding in December 2014;
- the central coast and southern Queensland trough in March 2014;
- the central and southern Queensland low from 25 February to 5 March 2013;
- Tropical Cyclone Oswald and associated rainfall and flooding in 21–29 January 2013;
- Roma flooding in early February 2012;
- Roma flooding in April 2011; and
- Roma flooding in March 2010 (with a 100-year return period).

The flood event in 2012 is considered to be the worst flood experienced in Roma's history, having inundated 444 homes (twice as many as were flooded in 2010). The boundary of the flood is illustrated in Fig. 7. According to the Queensland Reconstruction Authority, the Maranoa Regional Council's estimated that the public infrastructure damage from the natural disaster events of 2012 was approximately AUD 50 million. After the 2012 flood, and having experienced three sequential years of flooding, insurance companies claimed that issuing new policies to Roma residents was only dependent on

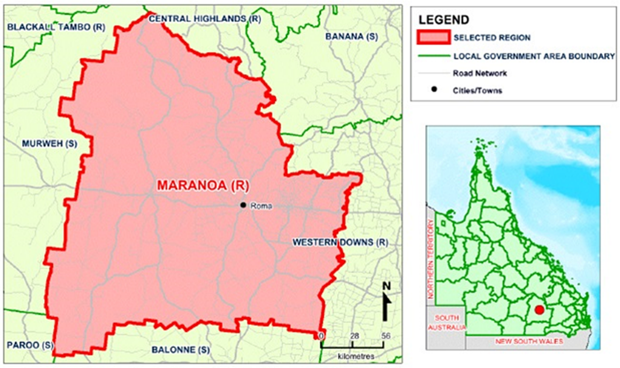

Figure 5. Map of Maranoa Regional Council (Queensland Government, 2011b).

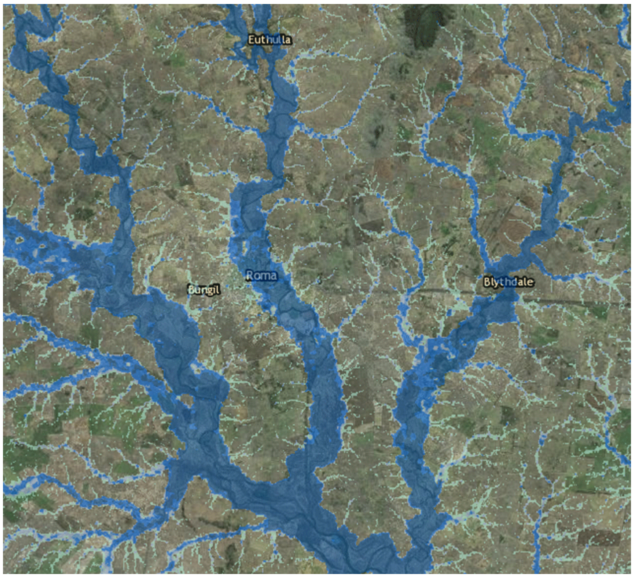

Figure 6. Basin-level flood modelling for Bungil Creek (Queensland Department of Natural Resources and Mines, 2015).

taking some new actions in regards to mitigating the risk of flood in this city.

4.2 Official flood loss data

Data collection on recent extreme events is a difficult procedure, even in some developed countries such as Australia. Damage surveys after a flood are not a common activity for governments, and they mostly rely on insurance company payouts or media reports for information (Bureau of Transport Economics, 2001; McBean et al., 1986; Merz et al., 2010; Smith, 1994). Insurance companies are mainly concerned with the collection of data on repair costs and their relation to the total insured value of the flooded object. However, data sets that were gathered with the aim of classifying structural damage or deriving loss estimation models also contain information about the flood characteristics, building types, construction materials, etc. (Thieken et al., 2009). In addition to these issues regarding the standards of data gathering, these companies do not distribute their detailed databases due to confidentiality policies. Usually their data are only available as a total value of consequences related to one specific event. On the other hand, data released by the media are not detailed as well as insurance records and cannot be considered as official and validated resources.

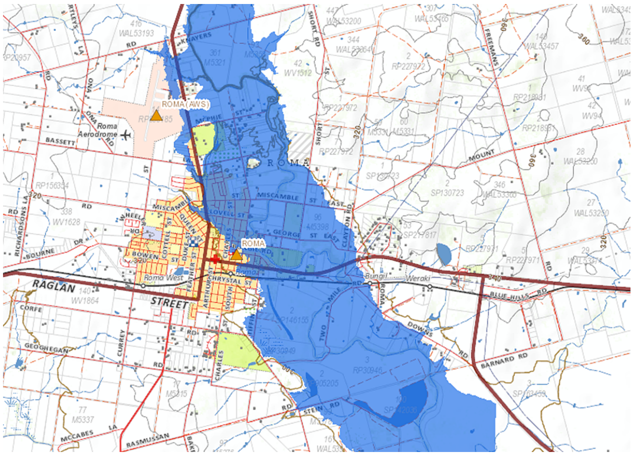

Figure 7. Boundary of the 2012 historic flood event (Queensland Department of Natural Resources and Mines, 2015).

4.2.1 Flood loss data of 2013

An official data set on the level of hazard, characteristics of buildings, and the magnitude of losses provided by the Queensland Reconstruction Authority were used to calibrate $\mathrm{FLFA_{rs}}$ developed in this study. This data set provides 592 data samples from the Bundaberg flood in 2013. After discarding the unrelated cases (buildings with irrelevant functions or characteristics), 319 final samples for the four selected building types were collected. For these samples, the impacts of flood have been presented by the depth of water above the first floor of the buildings. Furthermore, the vulnerability of the buildings has been shown by wall type (e.g. timber or brick), building use, and number of storeys.

In addition to hazard and vulnerability information, the level of structural damage has also been explained in the data set. This empirical data set, which has been collected by two post-disaster surveys, has categorised the condition of flooded buildings into undamaged, minor, moderate, severe, and total damaged rates. In addition, the guidelines of the survey describe these qualitative terms based on the affected assembly items. To be more precise, for each category of damage, it illustrates which groups of sub-assemblies (e.g. foundation, below first floor, structure, interiors and exterior walls) start to become damaged, or become partially or entirely damaged. Consequently, based on the sub-assembly approach proposed by the HAZUS technical manual (FEMA,

Table 1. Sub-assembly replacement values for the common types of residential buildings as a percentage of the total building replacement value (an average estimation based on Rawlinsons construction cost guide (2014) and local construction companies).

Assembly components	Relative value
Foundation	9 %
Below first floor	3 %
Structure framing	9 %
Roof covering and roof framing	7 %
Exterior walls	22 %
Interiors	50 %
Total	100 %

2012) and for exchanging the description of damages into percentage of damages, the following steps have been accomplished:

- For every type of building, the replacement value of each set of building sub-assembly compared with the total value of the building has been estimated. In that connection, the Australian construction cost guide (Rawlinsons, 2014) and cost estimation bills generated by local construction companies (e.g. Organized Builders' cost estimation: http://organizedbuilders.com.au/) were utilised. Table 1 summarises the average contribution of sub-assembly replacement values as a percentage of the total building replacement value.

- Based on the guideline descriptions of the damaged components and the relative value of affected items compared to the entire value of the building, damage description of each building has been exchanged to one percentage of damage.

- For every building, based on the estimated percentage of damage and the reported depth of water, the percentage of damage vs. depth of water has been illustrated. Percentages of damage vs. depths of water for all samples have been depicted in Fig. 8.

On the basis of sub-assembly values and guideline descriptions, Fig. 9 summarises the sub-assembly losses for one-storey buildings with timber walls. The vertical axis is the sub-assembly loss as a percentage of its own replacement value (extracted from the guideline descriptions), and the horizontal axis is the overall building loss as a percentage of the building replacement value (sum of the "sub-assembly losses multiplied by the average values").

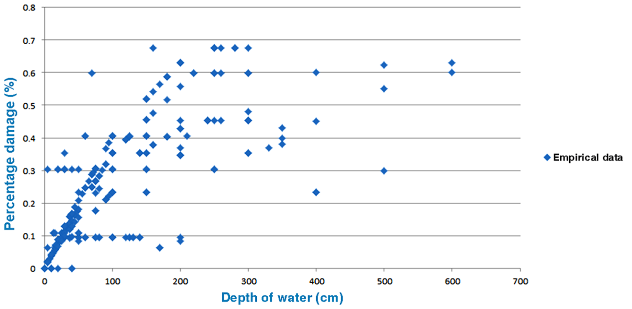

Figure 8. Empirical data points collected from 2013 Bundaberg flood event and utilised for calibrating $\mathrm{FLFA}_{\mathrm{rs}}$ (319 samples in 4 vulnerability classes).

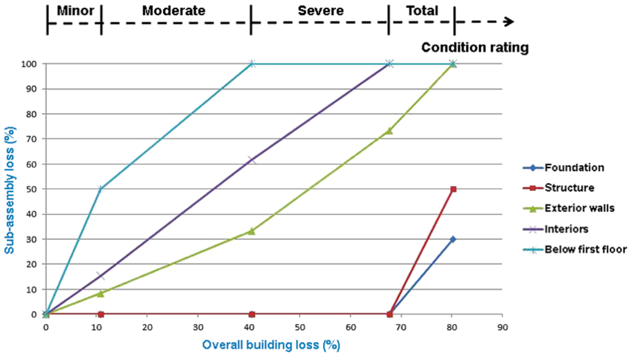

Figure 9. Illustration of condition rating and sub-assembly loss vs. overall building loss for one-storey buildings with timber walls on the basis of 2013 empirical loss data (based on building sub-assembly approach suggested by Hazus-MH Flood Model Technical Manual, FEMA, 2012). The horizontal axis is the overall building loss as a percentage of the building replacement value, and the vertical axis is the sub-assembly loss as a percentage of its own replacement value.

4.2.2 Flood loss data of 2012

To compare the performance of the applied damage models with the observed structural damages, an anonymised data set collected from the extreme event in the Maranoa region of Queensland, Australia (2012), has been utilised. This data set provides extent of damage, building type (e.g. wall type, number of storeys), and depth of water (i.e. flood level relative to first floor) for 150 inundated residential buildings (46 samples for one-storey buildings with timber walls; 14 samples for two-storey buildings with timber walls; 78 samples for one-storey buildings with brick walls; and 12 samples for two-storey buildings with brick walls). For every building, the absolute damage value has been calculated by multiplying the loss ratio by the average replacement value of each building extracted from the national exposure information system of Australia (Dunford et al., 2014). Resampling of all building loss values by means of bootstrapping was then carried out to obtain a 95 % confidence interval of the total observed losses. This was achieved with 10 000 simulated random samples which were drawn by replacement from the structural loss values. If the total losses estimated by the selected models fall within the 95 % interval of the resampled data, their performance will be assumed to be accepted; otherwise it can be rejected. By this approach, the performance of the applied damage models in terms of structural damage estimation in the area of study will be evaluated (Cammerer et al., 2013; Seifert et al., 2010; Thieken et al., 2008).

5 Derivation and calibration of $\mathrm{FLFA_{rs}}$ with the flood loss data of 2013

Flood losses could be related to a variety factors such as lateral pressure, velocity, duration, debris, erosion, and the chemical effects of water. However, the water depth is identified as the most dominant influencing factor of flood damage to residential buildings in short-duration riverine floods (Cammerer et al., 2013; Kelman and Spence, 2004; Merz et al., 2010; Thieken et al., 2005). Therefore, in the newly derived model, only the depth of water has been considered as the main characteristics of flood.

For the newly derived model in this work ($\mathrm{FLFA_{rs}}$), the extent of damage (d_h) in each stage of water (h) is a function of two different parameters: maximum percentage of damage $D_{\max}$, which represents the total percentage of damage corresponding to the maximum depth of water (maximum height of the building relative to the first floor); and the rate control of function r. For calibrating the model, these two parameters, with reference to the empirical data, should be fixed to the most appropriate values. However, due to the inherent uncertainty in the data sample, a range of estimates for the r factor and $D_{\max}$ have been provided. With this objective, this section of study has illustrated a bootstrapping approach to the empirical data to assist in describing confidence limits around the parameters of the depth–damage function. The following steps have been performed in this regard:

- Firstly, the empirical data set has been grouped into four different categories. This categorisation has been established according to considered vulnerability classes and building types.
- The range of maximum percentage of damage for each class of building has been selected (e.g. 60 to 80 % for buildings with timber walls). This selection has been made based on the scatter of empirical data and the Geoscience Australia report (Geoscience Australia, 2012).
- For every type of building, based upon the defined range of $D_{\max}$, different damage functions by different roots have been prepared.
- Based on the visual comparison among damage functions and the empirical data set, 210 different damage functions with the most appropriate values of r and $D_{\max}$ have been selected for each type of building. For instance, for one-storey buildings with timber walls, these 210 functions have been created by varying the r value between 1.1 and 2, and $D_{\max}$ between 60 and 80 %.
- Subsequently, resampling of empirical loss values by means of bootstrapping was carried out; with the help of chi-square test of goodness of fit, the best fitted values of r and $D_{\max}$ were extracted.
- Resampling of building loss values was continued up to 1000 times, and for each bootstrap the previous stage and goodness-of-fit test was performed. By this iteration, the average of fitted values of r and $D_{\max}$ converged to the optimal values used for the most-likely function. Also, the range of $D_{\max}$ and r parameters, which were used for generating the maximum and minimum functions, was extracted from the population of fitted values.

The range of estimates we are portraying with the $D_{\max}$ and r values express the lack of confidence in the damage–depth samples in representing the true uncertainty that exists in the population. Due to the fact that the relationship between flood impacts and losses to buildings is related to the characteristics of buildings (Cammerer et al., 2013; Thieken et al., 2005), these steps have to be repeated for all vulnerability classes and buildings types. Results of the model calibration are summarised in Tables 2 and 3. Furthermore, the final damage functions have been depicted in Figs. 10 and 11.

As can be seen from Table 3, for two-storey buildings, due to the different distribution and value of components in the height of the first floors in contrast to the second floors, different values should also be considered for the r and $D_{\max}$ factor of each storey. Referring to the higher rate of damage in the first floor of buildings compared to the second floor, the value of r in the first storey of buildings is expected to be more as well. This assumption is also reflected by statistical analysis. Although it would be more economical to replace a building that has more than 60 % damage rather than repair it (Nadal et al., 2010; Scawthorn et al., 2006), these damage curves have been extended up to the maximum value of damages for a better comparison with other models in the next part of this study.

6 Model comparison

6.1 Applied damage models

As mentioned earlier, since relative damage curves are more flexible in terms of transferability to a new area (Cammerer et al., 2013; Merz et al., 2010), besides $\mathrm{FLFA_{rs}}$, two more relative damage models have been selected for comparison in this study.

6.1.1 Geoscience Australia (GA) depth–damage function

Some generic depth–damage curves for south-east Queensland have been presented in the report by Geoscience Aus-

Table 2. Number of samples and range of r and $D_{\max}$ values, calculated by the bootstrap and chi-square test for one-storey buildings.

One-storey buildings					
Wall type	Number of samples	Parameters	Range of parameters		
			Minimum	Most-likely	Maximum
Timber	89	r $D_{\max}$	1.3 64 %	1.55 70 %	2 74 %
Brick	143	r $D_{\max}$	1.2 54 %	1.45 60 %	1.9 65 %

Table 3. Number of samples and range of r and $D_{\max}$ values, calculated by the bootstrap and chi-square test for two-storey buildings.

Two-storey buildings					
Wall type	Number of samples	Parameters	Range of parameters		
			Minimum	Most-likely	Maximum
Timber	49	r_1 r_2 $D_{\max 1}$ $D_{\max 2}$	1.5 1.3 38 % 25 %	2.3 1.5 42 % 28 %	2.4 1.55 43 % 28 %
Brick	38	r_1 r_2 $D_{\max 1}$ $D_{\max 2}$	1.4 1.2 32.5 % 25.5 %	2 1.4 34 % 26 %	2.3 1.5 36 % 28 %

Note: subscripts of r and $D_{\max}$ parameters represent the floor number.

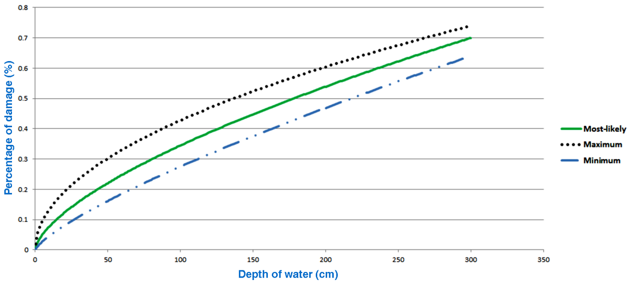

Figure 10. Visualisation of minimum, most-likely and maximum damage functions, calculated by bootstrap and chi-square test, for one-storey buildings with timber wall.

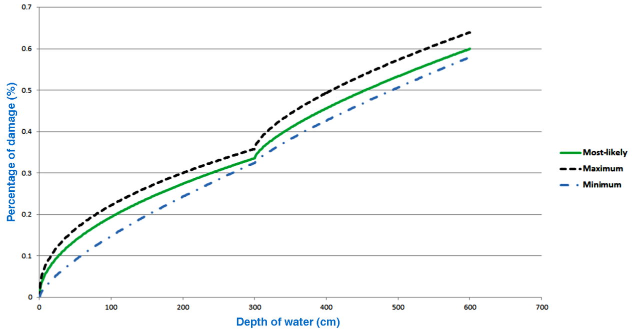

Figure 11. Visualisation of minimum, most-likely and maximum damage functions, calculated by bootstrap and chi-square test, for two-storey buildings with brick wall.

tralia (Geoscience Australia, 2012). These synthetic curves are prepared for estimating the magnitude of damage for building fabrics (including interiors) and building contents (including belongings that may be removed from the house) separately. Moreover, this report represents different curves for different vulnerability classes and building types based on the size of buildings, construction materials, the presence of garages, and the number of storeys (Geoscience Australia, 2012). It is worth noting that the performance of these synthetic damage curves has not been calibrated with any related empirical data sets. However, these damage curves are good examples for comparison for the following reasons: they express the magnitude of damages relatively; they are prepared by Geoscience Australia for use in our area of study; and they are prepared by the synthetic logic approach.

By taking the depth of water as the hydraulic input, this model gives the percentage of damage for every type of building separately. From this report, and with the aim of result comparison, four damage curves that are more related to the building types of this study have been selected.

6.1.2 FEMA/USACE depth–damage function

The United States Federal Emergency Management Agency (FEMA) and Army Corps of Engineers (USACE) provide stage damage curves for flood damage estimation of residential buildings. The functions are "relative" and damages are expressed as a percentage of total building value (USACE, 2003). Models are provided for one-storey or multi-storey buildings, with and without basements. Also, they represent the percentage of damage for the building's structure and contents separately (Comiskey, 2005). It is worth mentioning that similar to the GA approach, the structural curves cover all building fabrics, including interiors. Due to the frequent usage of the USACE model in Australia, this relative damage function has been selected for comparison in this study.

Similar to the other models, the only hydraulic input of these curves would be the depth of water. Also, the vulnerability classes considered in this method are related to the number of storeys and presence of a basement. From the provided curves by USACE, damage curves related to one-storey and two-storey buildings without a basement are the most appropriate and relevant curves for this study.

Visual comparisons of the depth–damage functions provided by the three methodologies are shown in Figs. 12 and 13.

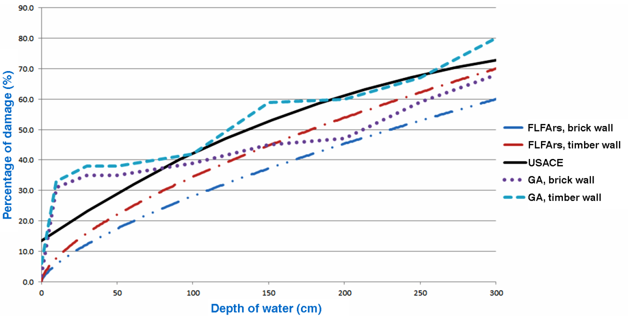

Figure 12. Model comparison for one-storey buildings (the FLFA$_{rs}$ has been derived by the most-likely functional parameters).

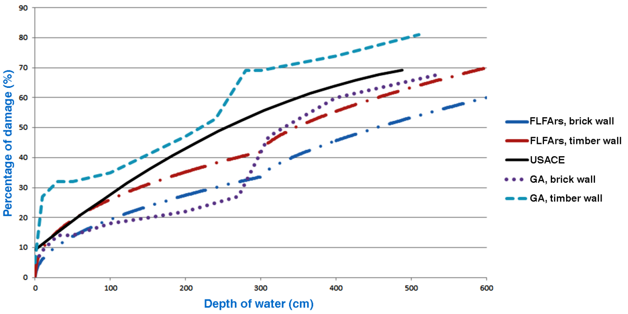

Figure 13. Model comparisons for two-storey buildings (the FLFA$_{rs}$ has been derived by the most-likely functional parameters).

6.2 Result comparison and model validation for the Maranoa study area

Results of applied damage models have been compared with the observed loss data collected from 2012 Maranoa flood event. As stated before, in addition to FLFA$_{rs}$ that has been calibrated with the damage data from the Bundaberg region, two more models (one local and one from USA) have been derived.

The overall reported loss for the 150 cases (building fabric) affected by the Maranoa flood amounted to AUD 13.17 million (mean of the 10 000 bootstrap samples), and the 95 % confidence interval ranges from AUD 13.03 million to AUD 13.32 million. As mentioned previously, if the estimated total losses by the selected models fall within the 95 % interval of the resampled data, their performance will be assumed to be accepted and sufficiently accurate; otherwise it is rejected (Cammerer et al., 2013; Seifert et al., 2010; Thieken et al., 2008). It is worth mentioning that for estimating the absolute value of damages for each building, the loss ratios extracted from the damage models have been multiplied by the same replacement values used in Sect. 4.2.2.

The performance of all flood loss models used to estimate the total building damage of the 2012 event is summarised in Table 4. It can be observed that the result of FLFA$_{rs}$ with the most-likely functional parameters lies within the confidence interval, and its performance may be acceptable. However, results of the GA and USACE models do not lie within the confidence interval of the reported loss and their performance is rejected in this area of study. This issue and the validation procedure illustrates the importance of model calibration with the empirical local data sets, particularly when the water depth is the only hydraulic factor considered (Cammerer et al., 2013; Chang et al., 2008; McBean et al., 1986).

Furthermore, errors in the estimates from the aforementioned models have been evaluated by the mean bias errors (MBEs), the mean absolute error (MAE), and the root mean square error (RMSE) statistical tests. The MBE provides the average deviation of the estimated ratios from the observed ratios and describes the direction of the error bias. A negative MBE indicates an underestimation in the estimated ratios, while a positive value shows an overestimation. The MAE represents the average absolute deviation of the estimated ratios from the observed values and is a quantity used to measure how close the estimates are to the empirical data. The RMSE also expressed the variation of the estimated ratios from the observed ratios, and it signifies the standard deviation of the differences between the estimated ratios and observed values (Chai and Draxler, 2014; Seifert et al., 2010). By these statistical comparisons, the performance of the derived models equated with the empirical data set has been

Table 4. Comparison of different loss estimates with the observed flood damage (95 % confidence interval) on residential building structures for the flood event of February 2012. Note: for model validation, FLFA$_{\mathrm{rs}}$ has been derived by the most-likely functional parameters.

Damage function	Estimated losses (in AUD million)	
FLFA$_{\mathrm{rs}}$	13.09	
GA model	25.42	
USACE model	20.21	
Reported loss in 2012	AUD 13.03 million (2.5th percentile)	AUD 13.32 million (97.5th percentile)

Table 5. Numerical comparison and error statistics of depth–damage function performance for the flood event of February 2012 (MBE: mean bias error; MAE: mean absolute error; RMSE: root mean squared error).

	FLFA$_{\mathrm{rs}}$	GA method	USACE method
MBE	−0.001	0.167	0.096
MAE	0.03	0.17	0.10
RMSE	0.04	0.19	0.11

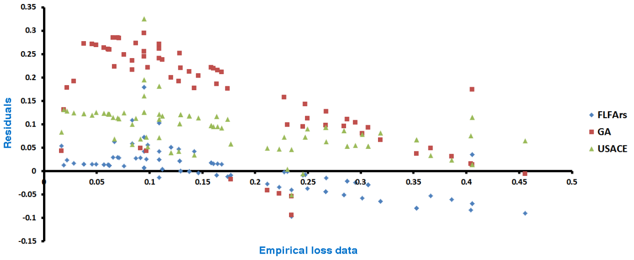

Figure 14. Residual plot used for comparing the performance of selected damage functions relative to empirical loss ratios.

assessed, and the results are summarised and compared in Table 5.

This table clearly shows that FLFA$_{\mathrm{rs}}$ has a better performance compared to other models. The MBE value shows a slight bias, very close to zero, for the newly derived model (FLFA$_{\mathrm{rs}}$), while this value for the other methodologies indicates a larger average deviation from the observed losses. On the other hand, the MAE and the RMSE for FLFA$_{\mathrm{rs}}$ estimates are 3 and 4 %, respectively. However, other models have larger average values of absolute deviation and greater values of standard deviation. This matter signifies a higher variation in the errors of the GA and USACE models estimates. As summarised in Fig. 14, the individual differences between the estimated ratios and observed values (residuals) in FLFA$_{\mathrm{rs}}$, in contrast to other methodologies, have less magnitude and variation. The FLFA$_{\mathrm{rs}}$ clearly achieves better results than the models which are not calibrated with the local damage data.

7 Conclusions

Damage mitigation and consequence reduction in terms of lessening the probability of expected losses is the main focus of risk management. While much effort has gone into emergency management in Australia, flood damage assessment is still crude and affected by large uncertainties. Stage damage curves are the most common and internationally accepted methods for flood damage estimation. Despite the simplicity of using these curves for different water depths, non-calibrated curves could considerably raise the level of uncertainty in flood damage assessment. Due to a lack of empirical data from recent extreme events, few studies have been conducted to explore the validation of well-known overseas methodologies in Australia. Also, most of the synthetic methodologies prepared for Australia are not calibrated with empirical loss data or express the magnitude of damage in absolute monetary values. These types of curves are not flexible for transferring in spatial scale or time, and their results are not reliable unless they have been calibrated with the conditions of the new region of study.

The focus of this study is on direct, tangible damages of four common types of residential buildings. This study aimed to present a new flood loss function for Australian residential structures (FLFA$_{\mathrm{rs}}$). The new function is a general methodology for describing the magnitude of damage for each stage of water, and suggests some simple and flexible curves with regards to the variability in characteristics of buildings. The FLFA$_{\mathrm{rs}}$ has been calibrated according to the geographical conditions in the area of study (i.e. building characteristics and flood specifications) using empirical data sets collected from the 2013 flood event in the Bundaberg region of Queensland, Australia. Finally, a statistical comparison for estimating the level of reliability and contrasting the performance of the methodology with damage data collected from the 2012 Maranoa flood event was conducted. With this objective and in addition to FLFA$_{\mathrm{rs}}$, a well-known overseas methodology and a local state approach were used for the area of study.

The analysis reveals that the results of the flood damage models are strongly dependent on the selected stage damage curves and flood damage estimation without model calibration might result in inaccurate values of losses. Therefore, it is very important to be aware of associated uncertainties in flood risk assessment if the loss functions have not been calibrated with the conditions of the region of study. The results of this study show that even the state methodologies might considerably overestimate the magnitude of flood impacts or significantly underestimate the value of losses if they have not been calibrated with the empirical loss data.

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