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Discussions

Results comparison and model validation for flood loss functions in Australian geographical conditions

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Abstract

Rapid urbanisation, climate change and unsustainable developments are increasing the risk of floods, namely flood frequency and intensity. 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.

This study aims to quantify the direct physical damage to residential structures that are prone to flood phenomena in Australia. In this paper, the physical consequences of two floods from Queensland have been simulated, and the results have been compared with the performance of two selected methodologies and one newly derived model. Based on this analysis, the adaptability and applicability of the selected methodologies will be assessed in terms of Australian geographical conditions.

Results obtained from the new empirically-based function and non-adapted methodologies indicate that it is apparent that the precision of flood damage models are strongly dependent on selected stage damage curves, and flood damage estimation without model validation results in inaccurate prediction of losses. Therefore, it is very important to be aware of the associated uncertainties in flood risk assessment, especially if models have not been adapted 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 probability of flood and the values of exposed properties have increased exponentially (Dewals et al., 2008; Elmer et al., 2012; Jalayer et al., 2013), which subsequently raises the significance of flood damage assessment. Flood damage assessment in terms of mitigating the probability of expected losses is the main 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 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. The function approach is a common and internationally accepted methodology for estimating the relative or absolute value of losses via a causal relationship between the magnitude of the hazard (e.g. the depth of water) and the level of vulnerability (e.g. the building type) (Dewals et al., 2008; Jongman et al., 2012; Kreibich and Thieken, 2008; Molinari et al., 2014b; Smith, 1994; Thieken et al., 2006). It is worth noting that these damage curves 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 validated with the conditions of the new region of study (Cammerer et al., 2013; Molinari et al., 2014b). On the other hand, flood actions on buildings could be related to a variety of hydraulic factors such as lateral pressure, velocity, duration, debris, erosion, and the chemical effects of water (Kelman and Spence, 2004; Merz et al., 2010; Thieken et al., 2005). But most of the models for direct impact estimation consider only the depth of water as the main characteristic of flood (Cammerer et al., 2013; Merz et al., 2010; Meyer et al., 2013). Overall, obtaining a reliable estimation of flood consequences by using a depth–damage curve with an accurate and validated 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 adaptability of well-known overseas methodologies to other regions (Cammerer et al., 2013), and also for validating local Australian methodologies with empirical data. This study aims to assess the applicability and transferability of overseas flood damage models to Australian geographical conditions by using historic data collected from 2012 and 2013 on extreme events in the Maranoa and Bundaberg regions of Queensland, Australia. In addition, the accuracy of the results obtained from a newly derived model and a local methodology were compared and evaluated using historic data. Although the simplicity of stage damage functions is the main reason for their common usage, neglecting some influencing aspects due to a lack of real damage data will raise the level of uncertainty (Cammerer et al., 2013).

2 Background

In addition to the Rapid Appraisal Method (RAM), which is an averaging methodology for damage estimation, there are a lot of depth–damage curves for flood loss assessment in Australia. The RAM is a simplified method for flood damage estimation in the absence of data required for using depth–damage curves. 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). Based on the synthetic approach proposed by Smith (1994), several local damage curves have been prepared for Queensland, Victoria and New South Wales. 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. 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). 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 assembly items and contents that are located above the basement (Barton et al., 2003). The magnitude of potential damage for different water levels via "what-if" questions is extracted based on their distribution in the height of the building and the level of vulnerability of each item (Gissing and Blong, 2004; Merz et al., 2010). As discussed further below, the newly derived model proposed in this paper has followed the logic suggested by Smith (1994). However, the authors have improved this model and compared it to existing Australian approaches.

Most of the synthetic methodologies prepared for Australia are not validated with empirical loss data, and few studies have been done on results comparison and uncertainty estimation. As mentioned earlier, the synthetic curves will estimate the potential damage based on "what-if" questions, which will give the maximum possible value of damage without considering any mitigating measures. Usually, potential damage is the greatest value of losses, and its magnitude is more than the actual damage (Molinari et al., 2013). Based on this, and for estimating the level of uncertainty, the results of the newly derived method and other models have been compared and validated with two actual and empirical databases.

Almost all of the approaches available in Australia express the magnitude of damage in absolute monetary values. These types of curves, compared to relative damage curves that show the magnitude of damage as a percentage, are less flexible for moving in the spatial scale or time (Merz et al., 2010). For instance, the RAM report (Sturgess and Associates, 2000) claims that the magnitude of damage estimated by ANUFLOOD curves should be increased by 60 per cent. 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. Therefore, transferring them to a new study area of Australia, the differences in the replacement value of the exposed items or repair costs of assets, will raise the level of uncertainty in 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 methods is observed by end users and researchers in Australia. To be more precise, a number of methods have been identified, such as the ANUFLOOD methodology, the Geoscience Australia model, and NSW government curves, but no specific literature has been published about them. However, the new method developed in this research, 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 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 Flood loss models

3.1 Geoscience Australia depth–damage function

Some comprehensive generic depth–damage curves for south-east Queensland have been presented in the report by Geoscience Australia (GA). 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 have not been compared or validated with any related empirical databases.

These damage curves are good examples for results comparison for the following reasons: they express the magnitude of damages relatively, they are adapted to our area of study, they are prepared by the synthetic logic approach, and they are supported by the Australian government.

3.2 The newly derived model

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; and
- Finally, based on the average value of the flooded items relative to the total value of the building, 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 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 validated with the relevant empirical datasets. To be more specific, four common vulnerability classes and building types for the selected area of study in Australia have been considered:

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

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

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

As discussed further below, this categorisation is totally adaptable with the empirical flood loss data. In other words, the empirical datasets have expressed the percentage of damage and the condition of flooded buildings based on the damaged sub-assembly groups.

The general methodology is to describe the damage for each stage of water quickly using a general function. Based on the recommendations of the HAZUS technical manual 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. 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 per cent of the total replacement value of the building. This means that for the first few metres of flood, the value of fragile exposure due to storing the utility facilities will increase greatly; while for the remaining distance, the rate of this change will be lower. 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:

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

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

In the above formula, the maximum value of damage for each class of building is extracted from the Geoscience Australia report (Geoscience Australia, 2012), which represents the value of damage corresponding to the maximum depth of water (maximum height of the building relative to the first floor).

By following the notion that in uniform residential buildings with more than one storey, the first floor of the building contributes more damage than the other stories because most utilities are stored there, this formula enables the user to define how much damage would occur between the first floor elevation, and how much damage can be distributed among the other floors. The generalised formula for damage estimation in each

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storey of a building based on the relative maximum value of damage and the appropriate value for rate control (r) can be expressed as:

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

where d_{hi} = percentage of damage corresponding to the depth of water above the ith floor, h_i = depth of water above the ith floor, H_i = height of ith floor, $D_{\max i}$ = maximum value of damage for the ith floor, and r_i = 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 validate this model easily based on the characteristics and types of buildings for other areas of study.

3.3 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 noting that similar to the GA approach, the structural curves cover all subassembly categories, including interiors. Due to the flexibility of the relative functions in transferring to a new area of study, the USACE model has been selected for this comparison. In the following parts, the adaptability and transferability of this method to Australian geographical conditions (characteristics of buildings and floods) with the help of GA curves and historic databases has been assessed.

4 Study areas and official data

4.1 Study areas and flood events

For this study, two homogeneous areas in terms of characteristics of buildings and flood impacts have been selected. The first study area is Bundaberg city in Queensland, Australia. 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 most recent flood responses from Bundaberg Regional Council date back to the floods in November 2010, January 2013, February 2013, and February 2015. As stated earlier, part of the empirical data used for this study has been collected after the January 2013 flood.

The flood events that occurred from 21 to 29 January 2013 were 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 from Burnett River reached 9.53 m at its peak, and over 2000 properties were flood affected (Queensland Government, 2013). 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 the Queensland Reconstruction Authority, Bundaberg Regional Council's estimated that the public infrastructure damage from the natural disaster events of 2013 was approximately AUD 103 million.

Another area of study is the city of Roma, located in the Maranoa region in Queensland. This town, as illustrated in Fig. 2, 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 is 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 that were flooded in 2010). According to the Queensland Reconstruction Authority, the Maranoa Regional Council 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 taking some new actions in regards to mitigating the risk of flood in this city.

4.2 Official flood dataset

Overall, 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 pay-outs or media reports for information (Bureau of Transport Economics, 2001; Merz et al., 2010; Smith, 1994). In addition to some issues regarding the standards of insurance companies that effect their methods of data gathering and collection (Thieken et al., 2009), 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.

In this study and for model validation, two official datasets on the level of hazard, characteristics of buildings, and the magnitude of losses, have been provided by the Queensland Reconstruction Authority. These spreadsheets provide data for 248 samples from the Bundaberg flood in 2013, and 150 samples from the Maranoa flood in 2012. After discarding the unrelated cases, 256 final samples for the four selected building types have been collected. It is to be noted that for selecting the most probable datasets, empirical samples with very rare population have been omitted from this group. This idea has been followed by the authors for minimizing the level of uncertainty of the empirical damage curve and having the most likely value for the rate control of the new method. 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 datasets. This empirical data, which has been collected for each flood event 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 and range of water depth. To be more precise, for each class of damage, it illustrates which groups of sub-assemblies (e.g. foundation, below first floor, structure, interiors and exterior walls) start damaging or become entirely damaged, and which interval of water depth this process will occur in. On the other hand, based on the earlier definition of sub-assembly groups, the replacement value of each group relative to the total value of the building has been estimated. This estimation has been done with the help of the Australian construction cost guide (Rawlinsons, 2014) and cost estimation bills generated by local construction companies (e.g. Organized Builders' cost estimation[1]). Table 1 summarises the contribution of sub-assembly replacement values as a percentage of the total building replacement value. Accordingly, based on the total value of affected items compared to the entire value of the building (Jonkman et al., 2008), each condition rate has been linked to one range of damage percentage and water depth (see Fig. 3). Finally, for every building, based on the magnitude of hazard and depth of water, the percentage of damage could be extracted.

5 Derivation of flood loss models to the study area

As discussed earlier, since relative damage curves are more flexible in regards to transferability to a new area (Cammerer et al., 2013) and are comparable with other methodologies, three damage models based on homogeneous logic have been selected for this section of the study. The first model has been provided by Geoscience Australia and contains 11 curves relevant to different types of buildings. 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 results comparison and model validation, four damage curves that are more related to the building types of this study have been selected.

[1] http://organizedbuilders.com.au/

Similar to the previous method, the newly derived model should provide four different stage damage curves for the selected types of buildings. In these models, only the depth of water as the main characteristic of short duration floods (Cammerer et al., 2013; Merz et al., 2010; Meyer et al., 2013) has been considered. As stated earlier, the first step of model derivation is choosing the maximum possible value of damage that can occur for each vulnerability class. These acceptable average values (80 % for timber buildings and 70 % for masonry buildings) have been extracted from state reports of Australia (e.g. GA report). In the next step and for two-storey buildings, the portion of each storey from the maximum value of total damage should be fixed. Due to the fact that the utilities of buildings (including mechanical and electrical facilities) are mostly stored on the first floor of buildings, and based on the replacement value of this equipment compared to other fragile items (e.g. the superstructure, exteriors and interiors excluding utilities), the magnitude of first floor damage relative to second floor damage can be estimated to be approximately 1.8 times more. Although it would be more economical to replace a building that has more than 60 per cent 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.

Finally, the most appropriate value should be selected for the root of function. Following an earlier explanation, the "r" factor is dependent on the distribution of components through the height of the building. For model validation, this root reference to the empirical data should be fixed to the most appropriate value. The statistical analysis presented in the next parts show that by considering an "r" factor equal to two for one-storey buildings, deviation of the damage model compared to the actual database would be less. However, this value would vary for two-storey buildings. 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. Eventually, compared to the empirical dataset, the most appropriate value for this root in the first storey would be four, while this value in the second storey is equal to two.

The last model, which has been compared with the historic data, is related to USACE damage curves. 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. 4 and 5.

6 Results

6.1 Statistical analysis for adapting the newly derived model with the observed losses

For selecting the most appropriate functions compared to the empirical data and validating the newly derived models, the following steps have been considered:

- For each type of building, different damage functions by different roots have been prepared.
- Therefore, by visual comparison between synthetic curves and empirical data, the damage curves with the most appropriate "*r*" factor have been selected. Also, due to the fact that synthetic curves usually represent the maximum value of losses (Molinari et al., 2013), the selected damage curves compared to the empirical data should portray a more conservative trend (Fig. 6).
- Since the focus of this study is on structure damages and there are fewer dramatic changes that can happen to the structural damage reduction with lead time, the authors have tried to select a conservative trend with a slight margin relative to

empirical datasets. In that connection, besides the visual comparison, the most accurate value of rate control has been selected by the chi-square test of goodness of fit. In this regard, selected curves from the previous step were examined by the chi-square statistical test, and the most appropriate one compared to the historic data was selected. For instance, although all visually selected curves for the one-storey buildings have fit very well with the empirical data, the probability of chi-square and the p value will be greater if the "r" factor is considered equal to two. This is summarised in Table 2.

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. Also, for two-storey buildings, due to the different distribution of components in the height of the first floors in contrast to the second floors, different values should also be considered for the "r" factor of each storey.

In this study, the water depth is considered to be the factor that most affects hazard; and the materials of buildings, absence of basement, number of storeys, and height of storeys have been considered as fragility characteristics of buildings (Kelman and Spence, 2004; Menoni et al., 2012). However, by adapting the loss functions with the empirical datasets collected from two homogenous areas with spatial variations, and providing empirically-based curves, damage models have been validated appropriately for use in the geographical conditions of the study area (Chang et al., 2008).

6.2 Results comparison for the derived functions

Deviation of results for the three derived functions relative to the historic datasets has been checked by comparing the average of the loss ratios and contrasting the coefficients of variation (CV). By this statistical comparison and for the four selected vulnerability classes, the performance of the derived functions equated with the empirical datasets have been assessed.

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In more detail, in order to develop some comparable ratios, all percentages of damage have been divided by the relevant values from the empirical datasets. The calculated ratios are less than one if the damage function represents a percentage of damage below the empirical data. Due to the fact that potential damage is the maximum possible value of losses without considering any mitigation measures (Bureau of Transport Economics, 2001; Molinari, 2011; Molinari et al., 2013), underestimated values which represent the percentage of damages less than actual values should be omitted for the averaging part. Although the newly derived function has been selected by considering this important matter, this issue has been carefully considered for GA functions and USACE results (as shown in Figs. 7 and 8). As can be seen from Table 3, the average values have been calculated from the ratios greater than one, and the standard deviation and coefficient of variation have also been estimated based on these ratios.

On the other hand, considering Figs. 7 and 8, all approaches overestimate the magnitude of losses for the first few centimetres of flood (approximately the first 15 cm). In other words, the ratio of losses in the minor category of damage is high and the level of uncertainty is considerable. Therefore, to account for this and to improve the performances of the models, the authors have excluded the data related to the first 10 cm of water depth in the numerical comparison. Numerical comparisons of the depth–damage functions provided by the three methodologies are shown in Table 4.

Table 4 clearly shows that the newly derived model represents lower values for the average of the loss ratios and they are closer to one (i.e. the loss ratio is equal to one if the results of the functions and empirical datasets match each other). This means that for the selected types of buildings, the performance of the new method related to historic data is more accurate (see Figs. 9 and 10). Considering Table 4, Figs. 9 and 10, we see that the newly derived model is also conservative, and marginally less than the results for the GA method and the USACE approach. On the other hand, the smaller values for standard deviation and coefficient of variation (CV) in the new method dataset shows that data points are less spread out from the average of loss ratio.

Furthermore, this table shows that the results of GA, especially for one-storey buildings, are slightly more conservative when compared with the USACE approach. Also, as stated before, both methods have a considerable number of loss ratios with values less than one. These issues could highlight the importance of model validation with the empirical local datasets, which has not been done for these two approaches.

Overall, the general trend of data points in the newly derived model, in contrast to other methodologies, has had an excellent fit with the direction of the empirical datasets. However, these methodologies do not estimate the magnitude of losses for the first few centimetres of water depth appropriately, and their estimations contain considerable levels of uncertainty. It is to be noted that the newly derived method, as opposed to other methodologies, is consistently overestimating damage with a slight margin, which reduces the likelihood of false positives for the decision makers. Other methodologies that represent unstable trends seem to be more uncertain and difficult for making decisions. Last but not least, for future events damage prediction the newly derived model does require some calibrating. However, authors do not believe that work needs to be done very frequently; since structures are relatively permanent.

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, invalidated 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 adaptabil-

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ity and transferability of well-known overseas methodologies to Australia. Also, most of the synthetic methodologies prepared for Australia are not validated 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 adapted and validated with the conditions of the new region of study.

This study aimed to investigate the applicability and adaptability of different flood damage models to Australian geographical conditions by using historic data collected from 2012 and 2013 on extreme events in the Maranoa and Bundaberg regions of Queensland, Australia. The focus of this study is on direct, tangible damages of four common types of residential buildings. With this objective, a well-known overseas methodology, a local state approach, and one newly derived function were used for the area of study. The new function is a general methodology for quickly 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 newly derived model has been validated for Australian geographical conditions by using empirical datasets collected from recent flood events. Finally, a statistical comparison and numerical analysis with regards to estimating the level of uncertainty and comparing the performance of the methodologies was conducted.

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 validation results 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 adapted and validated with the conditions of the new region of study. The results of this study show that even the state methodologies will express the results of flood damage conservatively, either underestimating values or sometimes producing marginally high values, if they have not been adapted with empirical datasets.

Acknowledgements. We would like to thank the kind supports of Simon Dorrington and Queensland Reconstruction Authority for providing us with invaluable resources and datasets.

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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 and below first floor	12 %
Structure framing	9 %
Roof covering and roof framing	7 %
Exterior walls	22 %
Interiors	50 %
Total	100 %

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Table 2. Chi-square values for different root functions.

One-storey buildings			Two-storey buildings		
Root Function (r)	Timber Wall	Brick Wall	Root Function (r)	Timber Wall	Brick Wall
1st storey = 2	0.88225	0.826355	1st storey = 4 2nd storey = 2	0.7	0.43
1st storey = 2.5	1.908985	1.731978	1st storey = 4.5 2nd storey = 2.5	0.821	0.51

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Table 3. Average of loss ratios and coefficients of variation for one storey buildings with timber walls.

Water Depth (cm)	Empirical Damage (O)	New Method (E1)	E1/O	GA Method (E2)	E2/O	USACE Method (E3)	E3/O
5.00	0.02	0.10	4.19	0.20	8.11	0.15	6.08
8.00	0.04	0.13	3.53	0.30	8.11	0.16	4.19
10.00	0.05	0.15	2.96	0.33	6.69	0.16	3.25
12.00	0.06	0.16	2.70	0.34	5.75	0.17	2.79
13.00	0.06	0.17	2.60	0.35	5.38	0.18	2.73
15.00	0.07	0.18	2.42	0.35	4.73	0.18	2.43
16.00	0.08	0.18	2.34	0.36	4.50	0.18	2.32
20.00	0.10	0.21	2.09	0.36	3.65	0.20	2.03
25.00	0.12	0.23	1.87	0.37	3.00	0.22	1.78
30.00	0.15	0.25	1.73	0.38	2.59	0.23	1.57
35.00	0.17	0.27	1.61	0.38	2.24	0.25	1.47
38.00	0.18	0.28	1.55	0.38	2.07	0.26	1.39
39.00	0.19	0.29	1.53	0.38	2.02	0.26	1.37
40.00	0.19	0.29	1.51	0.38	1.97	0.26	1.35
45.00	0.22	0.31	1.43	0.38	1.75	0.28	1.29
48.00	0.23	0.32	1.39	0.38	1.65	0.29	1.24
50.00	0.24	0.33	1.36	0.38	1.58	0.29	1.21
55.00	0.26	0.34	1.30	0.39	1.46	0.30	1.14
60.00	0.29	0.36	1.25	0.39	1.36	0.32	1.12
65.00	0.31	0.37	1.20	0.40	1.28	0.33	1.07
70.00	0.33	0.39	1.16	0.40	1.19	0.34	1.02
72.00	0.34	0.39	1.14	0.40	1.17	0.35	1.02
75.00	0.36	0.40	1.12	0.40	1.12	0.36	1.01
80.00	0.38	0.41	1.09	0.41	1.07	0.37	0.97
85.00	0.40	0.43	1.06	0.41	1.02	0.38	0.94
90.00	0.43	0.44	1.03	0.42	0.97	0.40	0.94
100.00	0.47	0.46	0.98	0.42	0.89	0.42	0.89
125.00	0.51	0.52	1.01	0.50	0.98	0.48	0.94
150.00	0.55	0.57	1.03	0.58	1.06	0.52	0.95
160.00	0.56	0.58	1.03	0.59	1.04	0.54	0.96
170.00	0.58	0.60	1.04	0.60	1.03	0.56	0.97
180.00	0.60	0.62	1.04	0.60	1.01	0.58	0.97
200.00	0.63	0.65	1.04	0.60	0.96	0.61	0.97
210.00	0.64	0.67	1.04	0.62	0.97	0.63	0.98
250.00	0.71	0.73	1.03	0.67	0.94	0.68	0.95
260.00	0.73	0.74	1.02	0.70	0.96	0.69	0.94
280.00	0.77	0.77	1.01	0.75	0.98	0.71	0.92
300.00	0.80	0.80	1.00	0.80	1.00	0.73	0.91
	Average	1.56		2.58		1.95	
	Standard deviation	0.77		2.14		1.23	
	C.V	0.49		0.83		0.63	

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Table 4. Numerical comparison of depth damage functions performance (by excluding the data related to the first 10 cm of water depth).

		New method	GA method	USACE method
One Storey Building with Timber Wall	Average	1.39	2.05	1.57
	Standard deviation	0.49	1.41	0.58
	CV	0.36	0.69	0.37
One Storey Building with Brick Wall	Average	1.45	2.84	1.57
	Standard deviation	0.55	1.67	0.68
	CV	0.38	0.59	0.43
Two Storey Building with Timber Wall	Average	1.37	1.87	1.63
	Standard deviation	0.57	0.84	1.29
	CV	0.41	0.45	0.79
Two Storey Building with Brick Wall	Average	1.20	1.35	1.37
	Standard deviation	0.35	0.47	0.59
	CV	0.29	0.35	0.43

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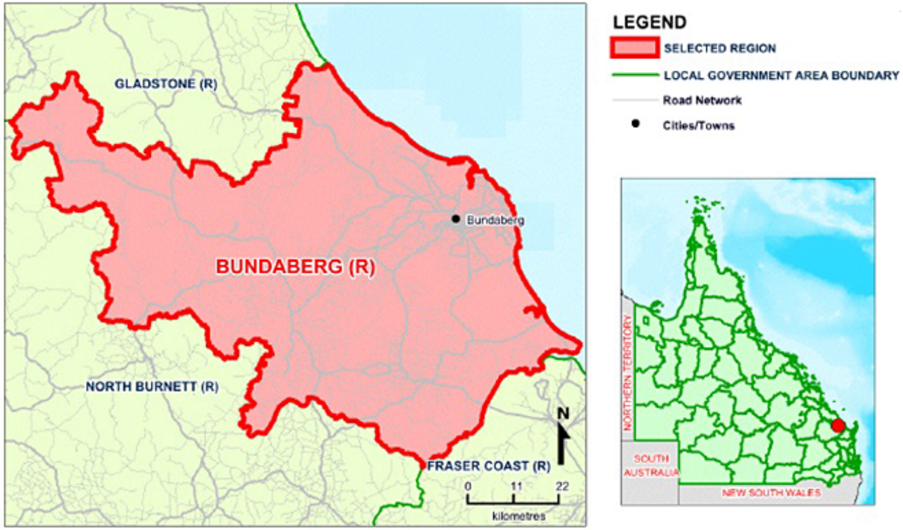

Figure 1. Map of Bundaberg Regional Council (Queensland Government, 2011a).

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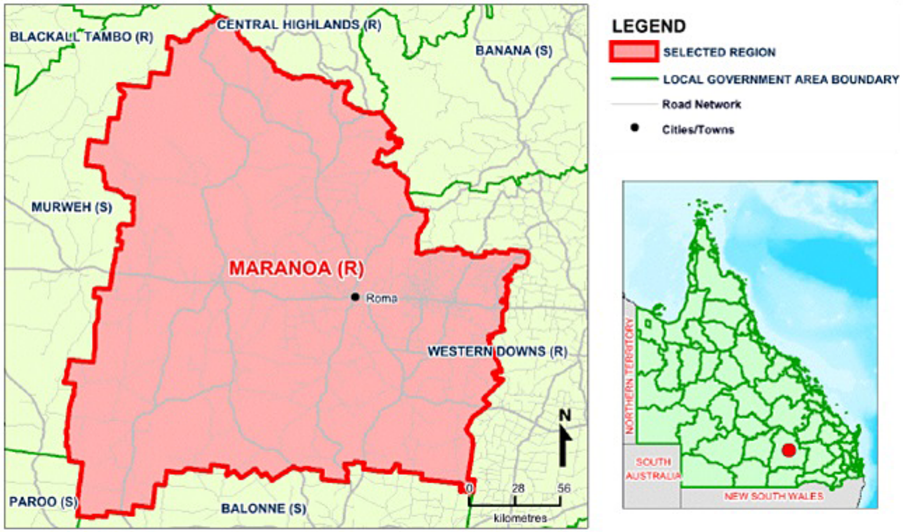

Figure 2. Map of Maranoa Regional Council (Queensland Government, 2011b).

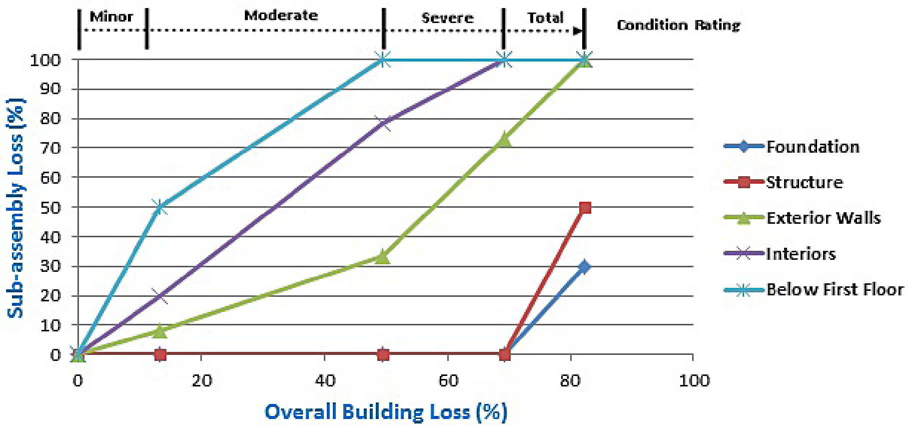

Figure 3. Illustration of condition rating and sub-assembly loss vs. overall building loss for one-storey buildings with timber walls (based on building sub-assembly approach suggested by Flood Model: Hazus-MH Technical Manual, FEMA, 2012).

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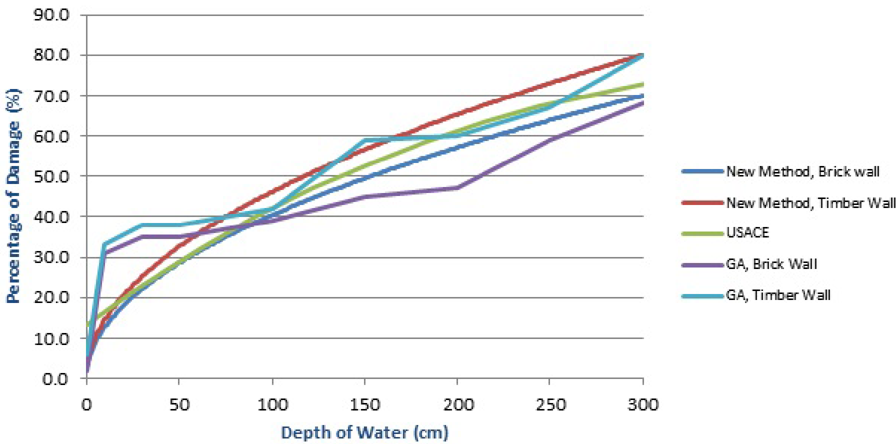

Figure 4. Model comparison for one-storey buildings.

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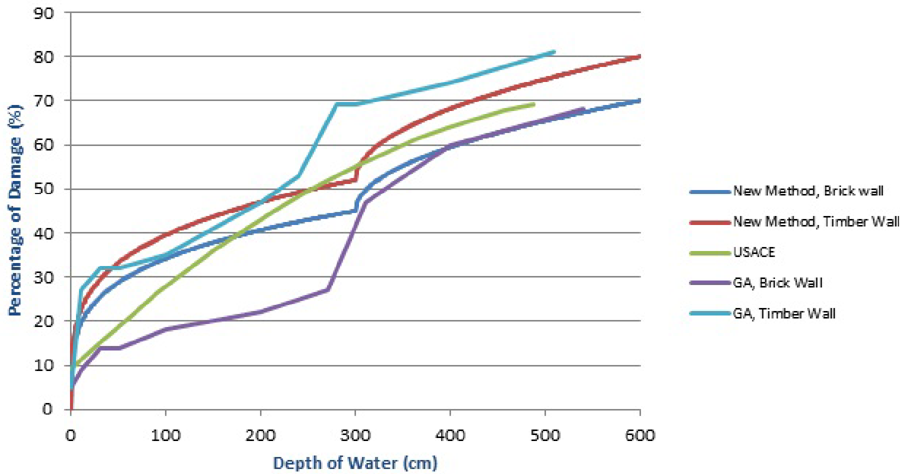

Figure 5. Model comparisons for two-storey buildings.

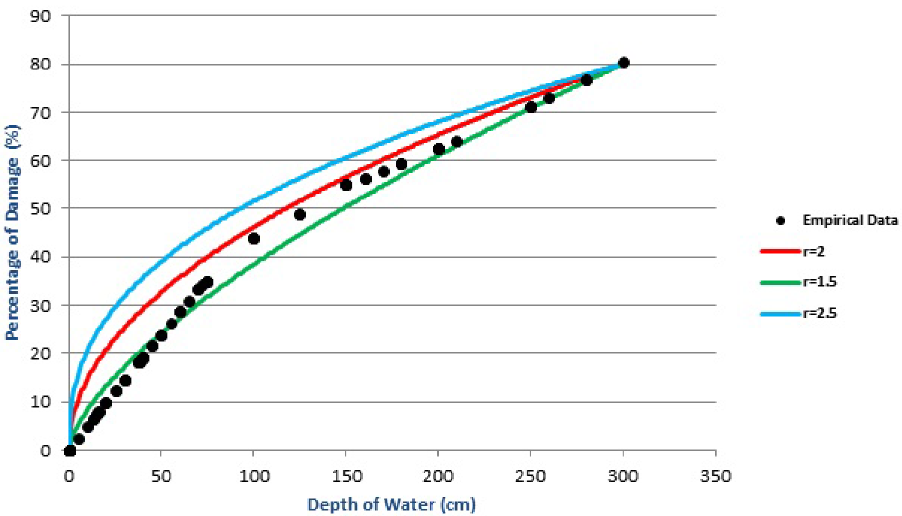

Figure 6. Visual comparison for one-storey buildings with timber walls.

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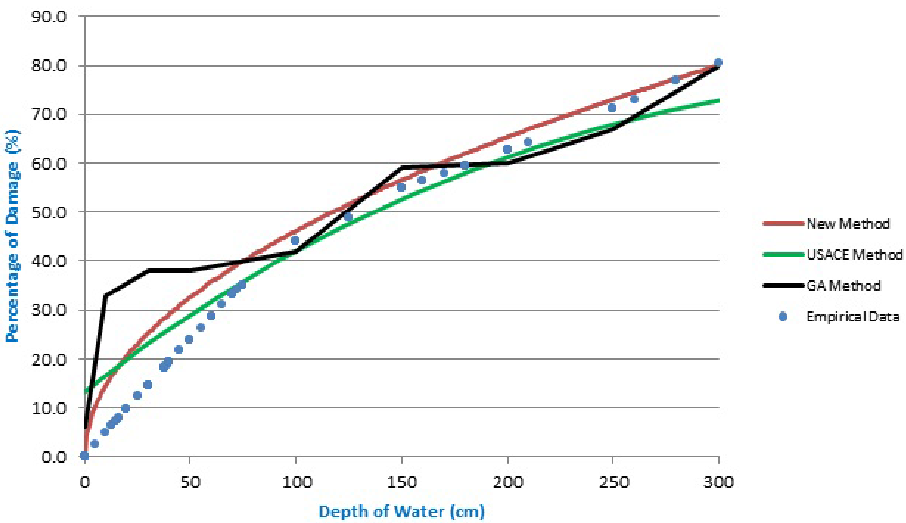

Figure 7. Performance of functions for one-storey buildings with timber walls.

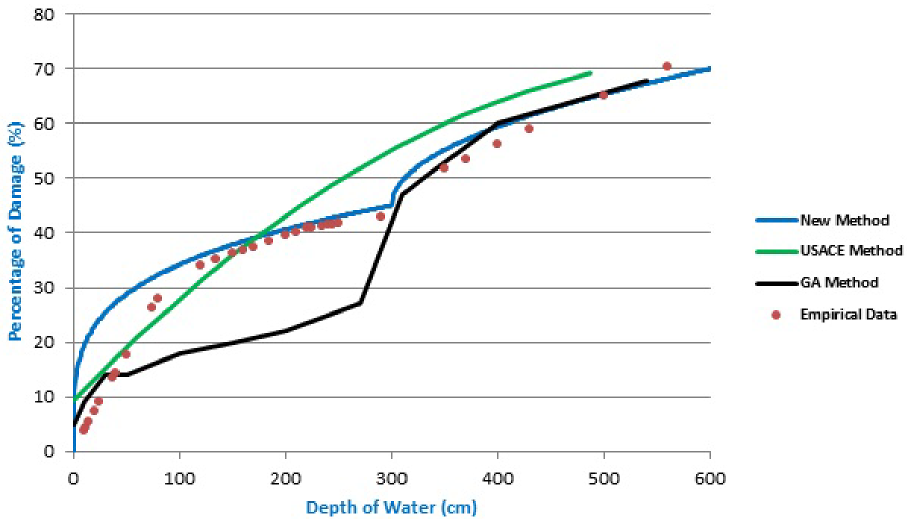

Figure 8. Performance of functions for two-storey buildings with brick walls.

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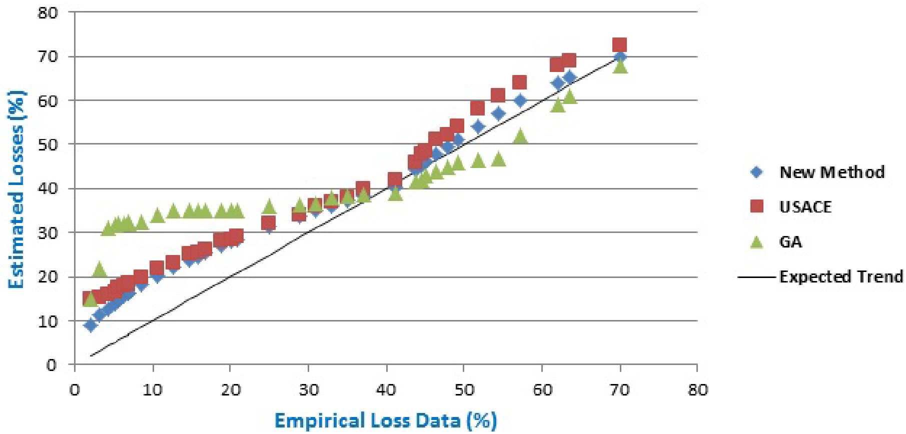

Figure 9. Comparison of observed damage data and estimates supplied by the selected methods for one-storey buildings with brick walls (suggested by Molinari et al., 2014).

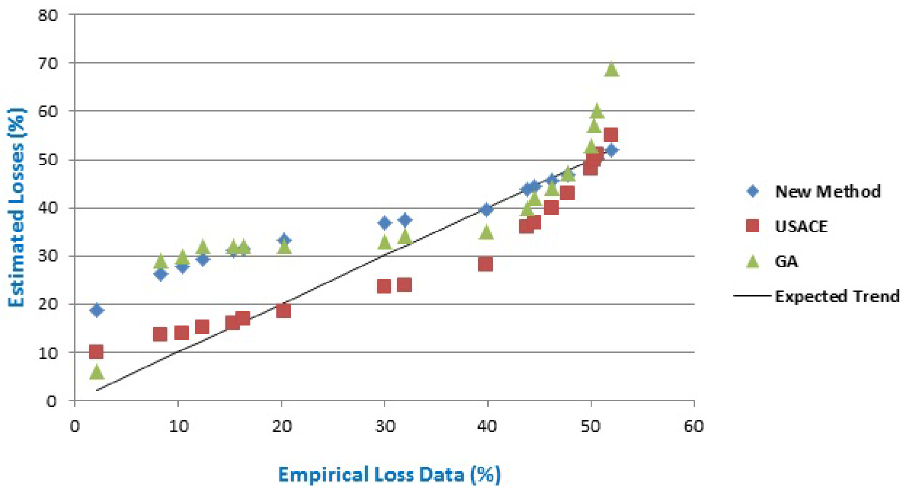

Figure 10. Comparison of observed damage data and estimates supplied by the selected methods for two-storey buildings with timber walls (suggested by Molinari et al., 2014).