Exploring Australian Hazard Map Exceedance Using an Atlas of Historical ShakeMaps

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Abstract

Seismic hazard models, commonly produced through probabilistic seismic hazard analysis, are used to establish earthquake loading requirements for the built environment. However, there is considerable uncertainty in developing seismic hazard models, which require assumptions on seismicity rates and ground-motion models (GMMs) based on the best evidence available to hazard analysts. This paper explores several area-based tests of long-term seismic hazard forecasts for the Australian continent. ShakeMaps are calculated for all earthquakes of M_W 4.25 and greater within approximately 200 km of the Australian coastline using the observed seismicity in the past 50 years (1970-2019). A “composite ShakeMap” is generated that extracts the maximum peak ground acceleration “observed” in this 50-year period for any site within the continent. The fractional exceedance area of this composite map is compared with four generations of Australian seismic hazard maps for a 10% probability of exceedance in 50 years (~1/500 annual exceedance probability) developed since 1990.

In general, all these models appear to forecast higher seismic hazard relative to the ground motions that are estimated to have occurred in the last 50 years. To explore aspects of possible prejudice in this study, the variability in ground-motion exceedance was explored using the Next Generation Attenuation-East GMMs developed for the central and eastern United States. The sensitivity of these results is also tested with the interjection of a rare scenario earthquake with an expected regional recurrence of approximately 5,000 - 10,000 years. While these analyses do not provide a robust assessment of the performance of the candidate seismic hazard for any given location, they do provide—to the first order—a guide to the performance of the respective maps at a continental scale.

Keywords: seismic hazard maps, ground-motion exceedance, ShakeMaps.

1 Introduction

Probabilistic seismic hazard assessments (PSHAs) are the most commonplace method to determine seismic demands for both national codes and standards, as well as for site-specific assessments for major infrastructure and other critical facilities. Since 1990, four widely cited continental-scale hazard assessments have been developed for Australia.

The PSHA methodology is defined such that the mapped hazard values will be exceeded at a pre-defined probability as required for the use-case of interest. For the Australian earthquake loading standard *AS1170.4–2018* (Standards Australia, 2018), this is defined as a 1/500 annual exceedance probability (AEP). In general terms, a 1/500 AEP means that in any 50-

year period, we should expect approximately 10% of the Australian continental landmass to experience ground shaking exceeding mapped values (e.g., Ward, 1995; Allen *et al.*, 2009; Vanneste *et al.*, 2018). Because the PSHA method explicitly allows for the mapped hazard values to be exceeded at a given probability level, it is expected that strong ground shaking could occur where mapped hazard is lower than the seismic demands that may be experienced at any given site (e.g., Hanks *et al.*, 2012).

Australia has a short historical record of seismicity relative to many regions globally and, in particular, relative to the return periods of large earthquakes on intraplate seismogenic faults (Clark *et al.*, 2012). Nevertheless, empirical studies indicate that large and potentially damaging earthquakes are more likely to occur in areas where there have been prior small earthquakes (e.g., Kafka, 2002). That is, the assumption that past seismicity is the best predictor for future seismicity holds true. That this is reasonable can be seen in that seismicity has remained relatively stationary in space and time in the historical era in the eastern highlands, the Flinders Ranges, and the northwest continental shelf region (Leonard, 2008; Griffin *et al.*, 2017).

In this paper, the ShakeMap software (Wald *et al.*, 1999; Worden *et al.*, 2017) is used to calculate the peak ground acceleration (PGA) shaking field for all earthquakes of M_W 4.25 and larger. A “composite ShakeMap” is developed that extracts the maximum PGA observed at any given grid location within the Australian continental landmass. The fractional exceedance area of this composite map is compared with four generations of Australian seismic hazard maps for a 10% probability of exceedance in 50 years (~1/500 annual exceedance probability) developed since 1990. The results are intended provide a guide as to the performance of the respective maps at a continental scale. These results are considered in the context of their uncertainties in earthquake occurrence, ground-motion and limited independent data.

2 Existing National Hazard Models

The *AS1170.4–2018* (Standards Australia, 2018) hazard design factors trace their lineage back to the probabilistic seismic hazard assessment (PSHA) of Gaull *et al.* (1990). This was a landmark study for its time and was developed based on scientific understandings and available data from the late 1980s. The Gaull *et al.* probabilistic assessment was subsequently modified through a process of expert judgement (McCue, 1993) for inclusion in the then new design standard *AS1170.4–1993* (McCue *et al.*, 1993). This hazard map compiled in 1991 was not a probabilistic assessment, but reflected the collective understanding of seismic hazard in Australia at the time and has guided engineering design since its publication. The McCue *et al.* (1993) hazard map also underpinned the Australian contribution to the 1999 Global Seismic Hazard Assessment Program (GSHAP; Giardini *et al.*, 1999; McCue, 1999). The McCue *et al.* (1993) hazard map is not a

Since the development of the 1991 hazard map, national-scale seismic models have been developed to support various national and site-specific hazard assessments and assessments developed for asset portfolios (e.g., Brown and Gibson, 2004; Hall *et al.*, 2007). However, these models were not developed specifically with building codes in mind. In 2012, Geoscience Australia (GA) released the National Seismic Hazard Maps (NSHM12) that were intended to supersede the 1991 seismic design factors in the Standard (Burbidge, 2012; Leonard *et al.*, 2013). This assessment used modern probabilistic methods, improved characterisation of tectonic region type and maximum earthquake magnitude (Leonard and Clark, 2011; Clark *et al.*, 2012) and included Australian-specific ground-motion models (Somerville *et al.*, 2009; Allen, 2012). In addition, the earthquake catalogue was augmented with a further 20 years of earthquake data (i.e., magnitudes and epicentres) relative to the 1991 assessments. The map used here was not strictly a probabilistic hazard map. It used a probabilistic “regional” layer, where the regional layer was greater than a “local” or “hotspot” layer and took the average of these two layers elsewhere (Leonard *et al.*, 2014).

A further effort to update national-scale seismic hazard assessments was completed in 2018 (Allen *et al.*, 2020). The National Seismic Hazard Assessment (NSHA18) built upon the NSHM12 by more fully exploring the epistemic uncertainties in seismic source characterisation through the use of third-party source models and weighting these models using a structured expert elicitation process (Griffin *et al.*, 2018; 2020). For the first time in Australia, a fault-source model was employed (Clark *et al.*, 2016), together with an earthquake catalogue consistently expressed in terms of moment magnitude (Allen *et al.*, 2018b). Ultimately, neither the NSHM12 nor NSHA18 were accepted for use in the Standard.

An additional study by Lam *et al.* (2016) recommended a uniform probabilistic seismic hazard that seismic hazard of 0.07 g was applicable for stable continental regions (SCRs). This study assessed the rate of magnitude 5.0 earthquakes in SCRs worldwide to determine an average PGA threshold that may be applied for codes and standards in regions of low seismicity.

A comparison of the Gaull *et al.* (1990), GSHAP (McCue, 1999), the NSHM12 (Burbidge, 2012; Leonard *et al.*, 2013), and the NSHA18 (Allen *et al.*, 2018a) mean PGA hazard maps with a 10% probability of exceedance in 50 years using a consistent colour palette is shown in Figure 1. In addition to these four models, the uniform hazard model of Lam *et al.* (2016) is also evaluated in terms of its exceedance rate below.

3 Method

ShakeMaps from the observed seismicity in the past 50 years (1970-2019) are calculated using the USGS' ShakeMap software (Wald *et al.*, 1999; Worden *et al.*, 2017) for all earthquakes of M_W 4.25 and greater within approximately 200 km of the Australian coastline. In total, ShakeMaps are calculated for 345 historical events. Earthquake source parameters were derived from the NSHA18 earthquake catalogue with magnitudes uniformly expressed in moment magnitude (Allen *et al.*, 2018b), augmented with recent events. The catalogue was not declustered of dependent events, meaning that the shaking distributions of aftershocks are considered in these analyses. For the surface-rupturing earthquakes occurring in this time period, mapped finite-source ruptures were used to estimate distance to rupture for the ground shaking. For events without mapped fault ruptures, a point source with the preferred longitude, latitude and depth was applied.

The mean PGA ground-shaking field was calculated using four of the highest weighted GMMs from the non-cratonic tectonic region type as selected from the NSHA18 expert elicitation (Griffin *et al.*, 2018), including the Atkinson and Boore (2006), Somerville *et al.* (2009) non-cratonic, Allen (2012) and Boore *et al.* (2014) at equal weighting. These are the same models currently being applied in GA's real-time ShakeMap system (Allen *et al.*, 2019). A uniform site condition with a time-averaged shear-wave velocity in the upper 30 m (V_{S30}) of 760 m/s—consistent with site class B_e in the *AS1170.4–2018* (Standards Australia, 2018) and that used by the NSHA18—is applied to all ShakeMaps. A composite ShakeMap is then compiled where the maximum PGA observed across a regular 0.05° grid was extracted from the event-specific maps. The fractional exceedance area of the composite ShakeMap relative to the four generations of national hazard models with a 10% probability of exceedance in 50 years, together with the uniform hazard model of Lam *et al.* (2016) is calculated. In this study, there is an expectation that the latest models should yield the exceedance rate closest to the 10% target given their advantage of using the most complete datasets and scientific knowledge.

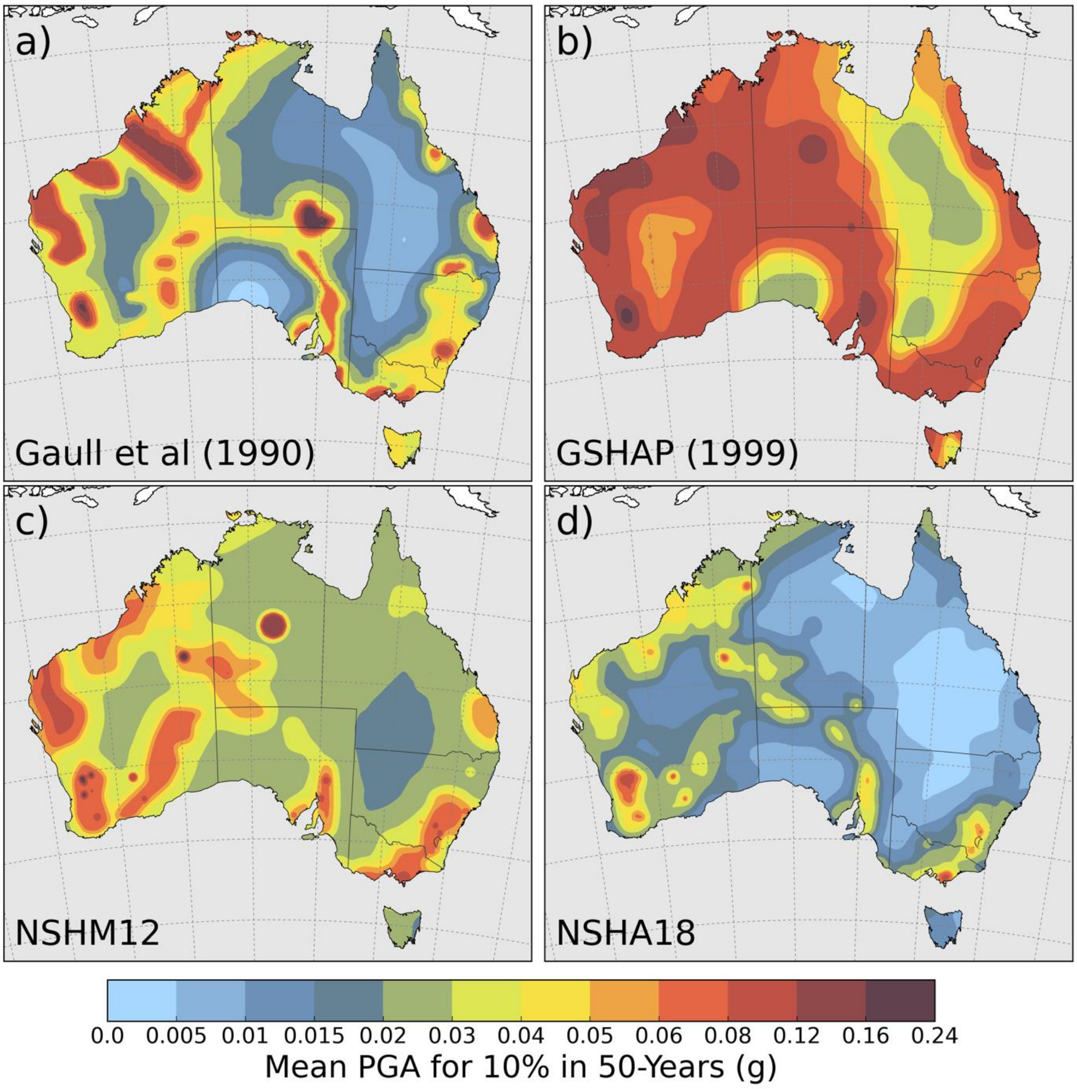

Figure 1: Comparison of four generations of seismic hazard maps showing mean PGA for a 10% probability of exceedance in 50 years. Maps include: (a) Gaull et al. (1990); (b) the GSHAP (McCue, 1999); (c) the NSHM12 (Burbidge, 2012; Leonard et al., 2013), and; (d) the NSHA18 (Allen et al., 2018a).

4 Results

The fractional area of exceedance for the respective hazard models are presented in three subsections. Firstly, an assessment of ground-motion exceedance is provided relative to the composite ShakeMap for the historical catalogue, 1970-2019. This first analysis uses GMMs preferred for use for Australian crustal conditions. Secondly, an alternative composite map that uses GMMs developed recently for the central and eastern United States (CEUS) (Goulet *et al.*, 2017) is applied as a worst-case scenario given the propensity of these CEUS GMMs' to overestimate PGA for Australian earthquakes (e.g., Hoult *et al.*, 2021). Finally, a rare scenario earthquake is supplemented with the Australian GMM composite ShakeMap. This is to assess the sensitivity of fractional exceedances in the event of rare, but plausible earthquake in low hazard regions that could occur by chance in the observation window.

4.1 Hazard Forecasts Compared with Historical Events

Figure 2a shows the composite ShakeMap showing the maximum observed PGA—based on GMMs preferred for use in Australia—from earthquakes of $M_W \geq 4.25$ for the 50-year period from 1970-2019. Using Generic Mapping Tools (Wessel *et al.*, 2013), ratios of the composite

ShakeMap relative to mapped 10% in 50-year PGA values for the Gaull *et al.* (1990), GSHAP, NSHM12 and NSHA18 models are shown in Figure 3. For all candidate hazard maps, it can be observed that the areas exceeding the mapped hazard values are generally quite small for most events and are localised at an earthquake's epicentre. The one exception to this observation is the exceedance levels observed for the 1988 Tennant Creek earthquake sequence in central Australia (Jones *et al.*, 1991), particularly for the Gaull *et al.* (1990) and NSHA18 models. For Gaull *et al.* (1990), the model-building process had been undertaken prior to the occurrence of the Tennant Creek earthquakes. Therefore, this model reflected the historical seismicity of the central Australian region prior to January 1988. Further discussion on the extent of the ground-motion exceedance for the Tennant Creek region in the NSHA18, given its use of a longer earthquake record, is provided in the Discussion section.

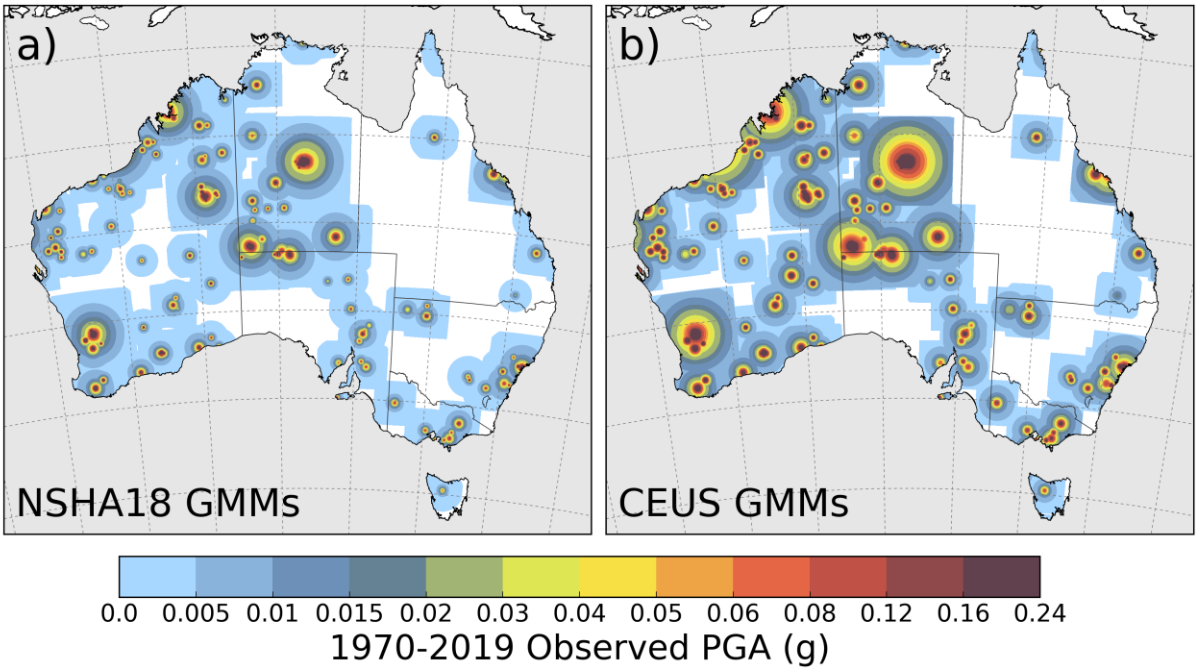

Figure 2: Composite ShakeMaps showing the PGA "observed" from earthquakes of $M_W \geq 4.25$ from 1970-2019 estimated using (a) preferred Australian GMMs and (b) GMMs used for hazard studies in the CEUS.

The fractional area of the Australian landmass which exceeds the mapped 10% in 50-year PGA values for each of the candidate models, including the uniform 0.07 g recommended by by Lam *et al.* (2016), is provided in Table 1. In general, all models appear to be conservative relative to the observed ground motions that are estimated to have occurred in the last 50 years. Fractional exceedances are found to be significantly lower than the expected 10% target rate for most models, particularly the GSHAP, NSHM12 and Lam *et al.* (2016) hazard forecasts. There are likely to be several reasons for these lower exceedance rates, which can be traced back to conservative decisions made during the model-building process. The Gaull *et al.* (1990) and NSHA18 appear to provide the greatest skill in forecasting the 10% exceedance rates on a national scale. However, they would both still be considered as conservative estimates of hazard forecasts given the past 50-year snapshot of national earthquake occurrence. For the NSHA18, there should be the expectation that this model should yield the exceedance rate closest to the 10% target given it has the advantage of using the most complete datasets and scientific knowledge of earthquake science in Australia.

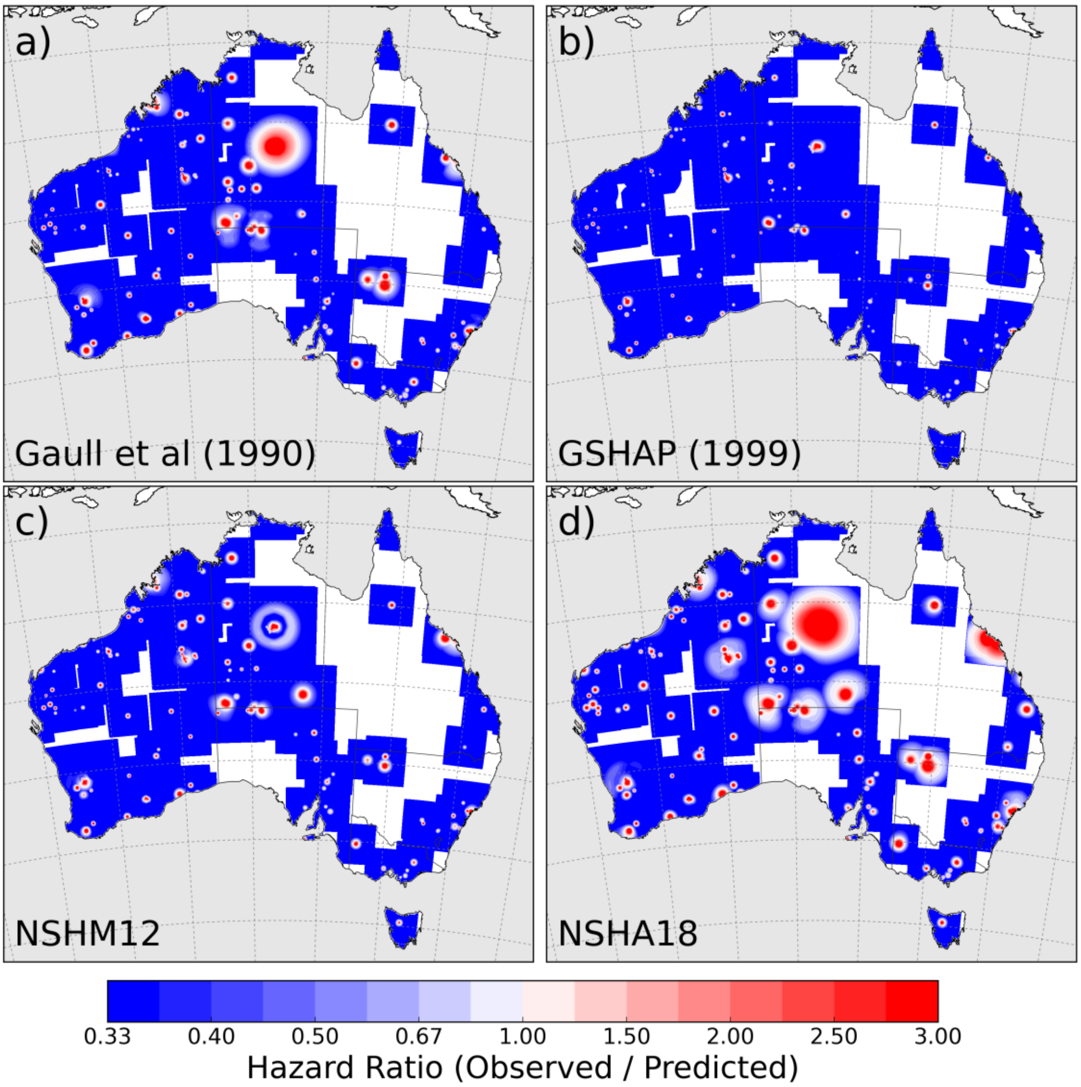

Figure 3: Ratios of the 1970-2019 composite ShakeMap to the estimates seismic hazard PGA for a 10% probability of exceedance in 50 years. Ratio maps are plotted for: (a) Gaull et al. (1990); (b) the GSHAP (McCue, 1999); (c) the NSHM12 (Burbidge, 2012; Leonard et al., 2013), and; (d) the NSHA18 (Allen et al., 2018a). The colour palette is truncated between ratios of 1/3 and 3.0.

4.2 Sensitivity to Ground-Motion Model Selection

Whilst it is not the intent of the authors to endorse a preference for GMMs developed for the CEUS, to explore the sensitivity in the results from the preceding section, the mean Next Generation Attenuation (NGA)-East GMM (Goulet *et al.*, 2017) is substituted in the ShakeMap calculation. Figure 2b shows the composite ShakeMap using the alternative GMM. What can be clearly observed is the lower rate of attenuation from an earthquake's epicentre, and consequent higher ground motions. Table 1 provides the fractional area of exceedance for the five 10% in 50-year hazard models. Using these GMMs, the exceedance rate is about a factor of three relative to that of the GMMs preferred for use in Australia.

Previous studies show that the CEUS typically demonstrates lower attenuation and larger ground motions relative to observational data from Australia (e.g., Bakun and McGarr, 2002; Allen and Atkinson, 2007; Hoult *et al.*, 2021). Consequently, the example shown here would represent a worst-case scenario in terms of ground-motion exceedances. However, it shows the sensitivity of hazard results to the selected GMMs in regions where relatively few near-source ground-motion recordings exist from moderate-to-large events from which to select and rank GMMs for hazard studies (e.g., Ghasemi and Allen, 2018).

4.3 Sensitivity to Rare Earthquakes

The above analysis relies on the assumption that the past 50-year record of seismicity in Australia is representative of the long-term rate of seismicity that might be expected in the future. Based on the historical observation window, we know that large-magnitude earthquakes can occur in locations with little to no historical evidence for seismicity. This presents a challenge to hazard modellers in striking a balance between providing realistic estimates of ground-motion hazard and not subjecting building designers and owners to design for high seismic demands that may have a very-low probability of occurring. As noted by Hanks *et al.* (2012), there are so many regions in the world characterised by low seismicity and seismic hazard that it is inevitable that when an earthquake occurs, the mapped hazard will be exceeded. Furthermore, the PSHA methodology is designed such that probabilistic ground motions will be exceeded with a given probability over a given time horizon—it is a statistical necessity. The area of exceedance can be minimised by reducing the exceedance probability for which the maps are developed (e.g., 2% probability of exceedance in 50 years).

In this section, a chance occurrence of a M_W 6.9 scenario on the Willunga fault added to the composite map of historical events (Figure 4). An event of this magnitude might be expected in the Adelaide region approximately every 5,000-10,000 years. Using the suite of GMMs preferred for use in Australia, the fractional area exceeding the mapped PGA values are calculated including this rare event with the national composite map (Table 1). An earthquake of this magnitude would clearly be devastating to the built environment of the local area. However, even its occurrence would not invalidate any of the models assessed herein, with each assessment remaining comfortably below the expected 10% exceedance rate for 50 years.

Table 1: Fractional area of landmass that exceeds the target 10% in 50-year PGA values for different event and ground-motion model combinations

Model	**AU GMM Percentage Exceedance**	**CEUS GMM Percentage Exceedance**	**AU GMM Percentage Exceedance (Adelaide Scenario)**
Gaull *et al.* (1990)	3.22%	9.63%	4.01%
GSHAP (1999)	0.63%	1.88%	0.74%
NSHM12	1.65%	6.14%	2.24%
Lam *et al.* (2016)	1.10%	3.18%	1.26%
NSHA18	6.94%	18.43%	8.40%

5 Assumptions and Limitations

As with any seismic hazard assessment, there are a number of assumptions and limitations embedded within this study that require disclosure. The key assumption herein is that the past 50-year earthquake history within Australia is representative of the long-term seismicity rate. In some regions across Australia, seismicity has remained relatively stationary in space and time (Leonard, 2008). However, we also know from rare events like the 1988 Tennant Creek earthquake sequence, that large events can occur in unanticipated locations. Hazard models are built acknowledging that these rare events may occur. There should also be recognition from end users that should these events occur, they will likely exceed the locally mapped hazard. Ideally, a study exploring the power of a probabilistic hazard forecast would require independent data for testing and validation (Gerstenberger *et al.*, 2020). Unfortunately, the short observation window and variable quality of earthquake catalogues (particularly earthquake magnitudes), precludes the inclusion of data for periods much earlier than approximately 1970.

Whilst progress has been made in characterising of ground-motion attenuation throughout the Australian crust in recent times (e.g., Somerville *et al.*, 2009; Allen, 2012), there does remain some uncertainty in the selection and use of GMMs in the Australian context. Whilst best efforts have gone into the selection of GMMs for generating the composite ShakeMaps in this study, the authors recognise that further work is required. As such, work is well underway to develop an Australian ground-motion database that will further improve the characterisation of GMM logic trees for future hazard assessments (Ghasemi and Allen, 2021).

Another limitation of this study is that far-field earthquakes in the Banda Sea region, that are regularly felt in northern Australia, have not been considered in the generation of the composite ShakeMap. A new GMM for earthquakes occurring in this region has been developed (Allen, in press), but has not yet been implemented into the ShakeMap algorithm. This may mean that there may be a slight underestimate in ground-motion exceedance rates for far northern Australian sites from historical events, but this is unlikely to affect the statistics significantly when considered at a continental scale.

Finally, there remain uncertainties in catalogue magnitudes, both through the correction of local magnitudes due to the use of inappropriate magnitude formulae (Allen, 2021) and through the conversion of local magnitudes to moment magnitudes (Allen *et al.*, 2018b), as required for generating ground-shaking fields in ShakeMap.

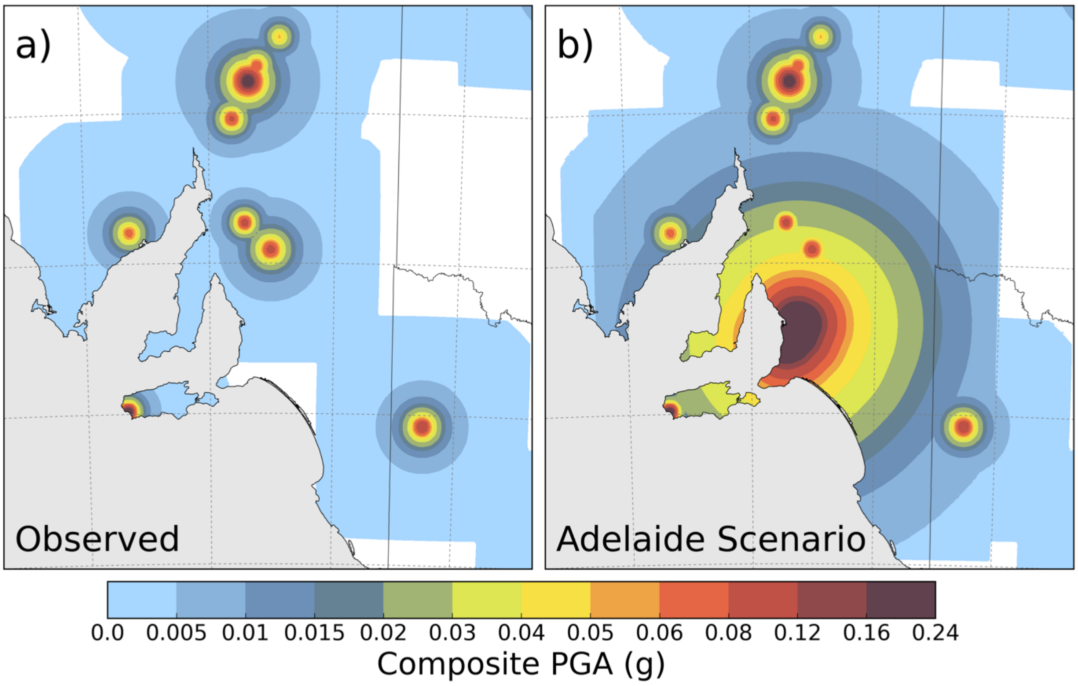

Figure 4: Composite ShakeMaps for the greater Adelaide region showing the (a) observed PGA from earthquakes of $M_W \geq 4.25$ from 1970-2020 estimated using preferred Australian GMMs and (b) a M_W 6.9 scenario on the Willunga fault added to the composite map of historical events.

6 Discussion

The performance of seismic hazard models is a key field of study for PSHA worldwide (e.g., Schorlemmer *et al.*, 2018). Given the role of PSHAs to establish earthquake loading requirements for the built environment, it is important to understand how skilled these models are at forecasting future earthquake shaking given the often-limited observations in the intensity range of interest. However, model validation is challenging given the scarcity of independent data (Gerstenberger *et al.*, 2020), particularly for site-specific assessments (Beauval *et al.*, 2008; Mak *et al.*, 2014). Since hazard models rely on historical data and knowledge, these same data cannot be used for prospective testing. However, they may be used to ensure a model is consistent with historical observations (Gerstenberger *et al.*, 2020).

Some studies have used macroseismic intensity or instrumental data to estimate ground-motion exceedance rates for given locations to assess the performance of national-scale models (e.g., Stirling and Petersen, 2006; Stirling and Gerstenberger, 2010; Griffin *et al.*, 2019). Indeed, in the present study, there are many sites that are likely to have been subjected to ground shaking from multiple events from 1970-2019 for which PGA return periods may be estimated. However, in a low seismicity region such as Australia, testing hazard at a given locality would require an observation window much longer than our instrumental records. Nevertheless, to a first order, it is possible to test performance of many points on aggregate to assess the overall performance of a PSHA over a broad region (e.g., Ward, 1995; Vanneste *et al.*, 2018). The current assessment serves as a useful retrospective test for the national-scale models to determine whether they are roughly consistent with their stated objective (i.e., that ground motions are exceeded with a given probability over a given period of time) rather than grossly over- or underestimating ground-motion exceedances.

One of the most obvious relative changes in the most recent national hazard assessment—the NSHA18—is the difference in hazard forecasts in the Tennant Creek, Northern Territory, region. Relative to previous hazard assessments (McCue *et al.*, 1993; Burbidge, 2012; Leonard *et al.*, 2013), the NSHA18 demonstrates significantly lower seismic hazard for this region, which in 1988 was subjected to three large earthquakes exceeding M_W 6.0 (Jones *et al.*, 1991), with aftershocks continuing to the present day. One might ask that with the benefit of hindsight, why does the NSHA18 have the largest area of exceedance in the Tennant Creek region? There are two main reasons for the relatively low hazard in the region: firstly, the PSHA methodology assumes earthquakes occur randomly in space in time (i.e., they follow a Poisson distribution). Consequently, standard PSHA practice is to decluster earthquake catalogues of dependent events (i.e., foreshocks and aftershocks). However, this significantly reduces the hazard in regions such as Tennant Creek. The declustering algorithm used in the NSHA18 (Allen *et al.*, 2018b) effectively reduces this region to one earthquake; the M_W 6.6 mainshock on 22nd January 1988. Consequently, there are few other earthquakes in the immediate vicinity that contribute to the region's earthquake rate model. Secondly, the fault-source used in the NSHA18 that represents the Tennant Creek scarps is assigned with very low slip rates (Clark *et al.*, 2016). These slip rates that are based on paleoseismic information (Crone *et al.*, 1997), mean that the fault-source does not contribute significantly to seismic hazard at ground-motion exceedance probabilities of engineering significance. This is consistent with other fault scarps in cratonic regions of Australia that have been studied in detail, which either show no evidence for recurrence, or evidence for limited recurrence of large events (Clark *et al.*, 2020).

Following from the previous discussion on the Tennant Creek earthquakes, there is growing evidence to support the notion of "one-off" ruptures in cratonic regions of Australia (Clark *et al.*, 2020; King *et al.*, 2021). Therefore, we may expect that large infrequent earthquakes (possibly exceeding magnitude M_W 7.0) could occur in an unanticipated location that is currently characterised by low seismicity and seismic hazard. When modelling seismic hazard in these settings, large background area-source models are commonly used to allow for large earthquakes to "float" over wide spatial regions at low probabilities of occurrence (e.g., Lam *et al.*, 2016; Allen *et al.*, 2020). These infrequent earthquakes will cause shaking much stronger than mapped probabilistic values (Hanks *et al.*, 2012; Vanneste *et al.*, 2018). However, these exceedances do not invalidate the PSHAs since hazard maps are designed to be exceeded for at a certain probability over a given period. The study of Vanneste *et al.* (2018) used a Monte Carlo approach to simulate thousands earthquake histories for a 50-year period. This study found that the fractional area of a uniform hazard model would exceed the predetermined exceedance probability for approximately 50% of the simulations, with larger variances expected in low-seismicity regions and higher probabilities of exceedance. Thus, whilst not ideal from a life safety perspective, even small overestimates of the objective exceedance rate should not invalidate national-scale hazard models.

7 Conclusion

A "composite ShakeMap" was generated from earthquakes of M_W 4.25 and greater affecting the Australian landmass in the 50-year period from 1970-2019 (Figure 2a). The maximum PGA "observed" across Australia for this period was used to assess the forecasting power of several generations of national-scale seismic hazard models for a 10% probability of exceedance in 50 years. Whilst there are a number of assumptions in this assessment and a lack of independent data for testing (particularly the more recent models), these analyses—to the first order—do provide a guide to the performance of the respective maps at a continental scale. Based on the assumptions described in this paper and the observed seismicity in the past 50 years, all national models considered herein are conservative in terms of the fractional area of landmass for which PGA has exceeded the mapped hazard. In particular, the GSHAP hazard map (McCue, 1999), which was adapted from the map used as the basis for the *AS1170.4–1993* (McCue *et al.*, 1993) and underpins the hazard design factors in the 2018 amendment to the Standard (Standards Australia, 2018), is the most conservative hazard assessment with a fractional exceedance of less than one-tenth of the expected exceedance rate of 10%. The model with the highest apparent skill at forecasting ground-motion exceedances is the NSHA18 (Allen *et al.*, 2018a). However, this should be expected given the similar assumptions in ground-motion estimation between the assessments and there are significant overlaps between the data used to build and test the model.

The sensitivity of these analyses is explored using alternative GMMs to characterise the attenuation for the individual ShakeMaps. Ground-motion models developed for the stable continental CEUS are substituted for the preferred suite of GMMs for Australia (Figure 2b). The CEUS models generally estimate larger accelerations and lower attenuation than would be expected from earthquakes in the Australian crust (e.g., Allen and Atkinson, 2007; Hoult *et al.*, 2021). As expected, the use of the CEUS GMMs leads to higher fractional exceedances for all models; particularly the NSHA18. While the seismological community has developed a better understanding of ground-motion attenuation in Australia, it is clear that this remains one of the most uncertain and influential aspects for seismic hazard assessments in Australia.

Finally, the models are tested with the insertion of a rare earthquake with a recurrence longer than the typical time horizon of building codes. A M_W 6.9 event is modelled on the Willunga fault near Adelaide (Figure 4b). Whilst an earthquake of this magnitude would be devastating to the built environment of the local area, its occurrence would not invalidate any of the models assessed herein, with each assessment having more than 90% of the continent below the expected 10% exceedance rate for 50 years.

Finally, modern seismic hazard assessments for Australia suggest that some regions are characterised by particularly low earthquake activity rates and consequent low probabilistic hazard. In these cases, seismic demands calculated through PSHA are unlikely to provide reasonable protection to a structure and its occupants in the event of a strong earthquake.

Therefore, complimentary approaches are available, such as the use of a floor in the seismic demands, to provide a minimum level of protection to structures.

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