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# THE 2023 UPDATE TO THE AUSTRALIAN NATIONAL SEISMIC HAZARD ASSESSMENT (NSHA23): PHILOSOPHY AND MODEL CHANGES

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**Abstract**: *The Australian National Seismic Hazard Assessment (NSHA) was updated in 2023 to coincide with the revision of the Australian Standard for the structural design actions for earthquake (AS1170.4). This updates the 2018 NSHA (NSHA18), which applied globally accepted, best-practice probabilistic approaches and yielded considerably lower hazard estimates at the 1/500 annual exceedance probability relative to previous national assessments and the AS1170.4–2007 seismic design values. Whilst the science underpinning the NSHA18 has withstood on-going peer review and critique, Geoscience Australia has reflected on this model and has advocated for adjustments to modelling choices where warranted. The use of structured expert elicitation was a major advance in the development of the NSHA18 and promoted ownership of the model amongst the Australian seismological community. However, some consequences of the modelling choices made during that process were not fully appreciated at the time. The 2023 NSHA (NSHA23) was intended to be a modest update to the 2018 model and again is characterised through structured expert elicitation. However, there are some key changes to the earthquake catalogue, which include: 1) the inclusion of events from mid-2017 through to the end of 2022; 2) the recalculation of local magnitudes for recent events (2010 onwards) to resolve recently discovered inconsistent observatory practice by different Australian monitoring agencies and errors with station metadata, and; 3) the subsequent revision of local magnitude to moment magnitude conversions. All seismic source models in the updated NSHA23 that rely on the updated earthquake catalogue (pre-instrumental and instrumental) are updated to reflect these changes. Incremental updates to the fault-source model and changes to the relative weights between different source-model class types have also been implemented. Another significant advance is the augmentation of the Australian Ground-Motion Database with new and legacy data. High-quality data acquired from Australian earthquakes since 2018 were used to enable more informed choices for the ground-motion characterisation model. In summary, the 2023 updates to the instrumented earthquake catalogue have led to reduced earthquake rates and seismic hazard. This change is counteracted using an updated suite of ground-motion models. Adjustments to weights in the source characterisation model yield spatially variable changes in hazard, most commonly leading to modest increases in hazard.*

## 1. Introduction

Forecasting seismic hazard in stable continental regions (SCRs) brings unique challenges to hazard modellers and practitioners in terms of the characterisation of seismic sources and their ground motions. By their very nature, SCRs experience significantly lower rates of seismicity compared to tectonic plate margins. Damaging earthquakes in Australia and other regions characterised by low seismicity are often considered low probability but high consequence events.

An updated National Seismic Hazard Assessment of Australia was released in 2018 (the NSHA18). Relative to the seismic hazard map included in the Australian earthquake loading standard—the *AS1170.4–2007* (Standards Australia, 2007)—which was based on the map of (McCue et al., 1993), the NSHA18 leveraged advances in earthquake-hazard science, both in Australia and analogue tectonic regions, that had occurred over the preceding three decades to offer many improvements over its predecessors. The outcomes from the NSHA18 represented a significant shift in the way national-scale seismic hazard was modelled in Australia, and consequently challenged long-held notions of seismic hazard amongst the Australian seismological and earthquake engineering community. Concerns regarding the robustness of the NSHA18 were raised (e.g., Dimas, 2020) given the significant reduction in the NSHA18 hazard levels relative to the hazard in the *AS1170.4–2007* (Allen, 2020; Allen et al., 2023a). These factors have led to some caution in the acceptance of the NSHA18 and its derivative products.

Since the NSHA18's completion, Geoscience Australia has reflected on the choices made both through the structured expert elicitation process and through decisions made by the NSHA18 team (Allen et al., 2020b; Griffin et al., 2020). The consequences of some choices on the production of the final seismic hazard model may not have been fully appreciated prior to embarking on the development of the NSHA18, nor during the expert elicitation workshops. The development of the NSHA18 revealed several philosophical challenges in terms of characterising seismic hazard in regions of low seismicity such as Australia. Chief among these are: 1) uncertainties in the rupture characteristics of neotectonic faults; i.e., do they follow Gutenberg and Richter (1944)-type or characteristic-type (Youngs and Coppersmith, 1985) magnitude-frequency distributions; 2) processes for the adjustment and conversion of historical earthquake magnitudes to be consistently expressed in terms of moment magnitude; 3) the relative weighting of different seismic-source classes (i.e., *background*, *regional*, *smoothed seismicity*, etc) for different regions and exceedance probabilities; 4) the assignment of Gutenberg-Richter *b*-values based on recurrence statistics determined from broad neotectonic domains (Clark et al., 2012), and; 5) the characterisation and assignment of ground-motion models used for different tectonic regimes (Ghasemi and Allen, 2018; 2022).

The 2023 National Seismic Hazard Assessment (NSHA23) addresses a number of the abovementioned themes through advances in scientific knowledge and through expert elicitation. The NSHA23 process was initiated through a request from the Standards Australia BD-006-11 sub-committee that is responsible for updating the structural design actions for earthquake in Australia (AS1170.4; Standards Australia, 2018). This paper summarises the development of the NSHA23, provides comparisons to previous national-scale hazard assessments and provides probabilistic seismic hazard factors to be considered in the revision of the *AS1170.4*.

## 2. Summary of Previous Hazard Models

Several manuscripts provide excellent summaries of the history of seismic design and code development in Australia (e.g., Brown and Gibson, 2004; McPherson et al., 2011; Woodside and McCue, 2017), through to the Standards Australia *Structural design actions, part 4: Earthquake actions in Australia (AS1170.4–2007 [R2018])*. The objective of the *AS1170.4* (Standards Australia, 2018) is to:

> *"provide designers of structures with actions and general detailing requirements to protect life and property from earthquakes".*

The *AS1170.4–2007 [R2018]* (Standards Australia, 2018) hazard design factors trace their lineage back to the PSHA of Gaull et al. (1990). This was a landmark study for its time and was developed based on scientific understandings and available data up to the late 1980s. The Gaull et al. (1990) probabilistic assessment was subsequently modified through a process of expert judgement (McCue, 1993) for inclusion in the *AS1170.4–1993* design standard (McCue et al., 1993). This hazard map, compiled in 1991, was not a probabilistic assessment, but reflected the collective understanding of earthquake occurrence and seismic hazard at the time and has guided engineering design in Australia 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).

Since the development of the 1991 hazard map, national-scale models have been developed to support various national and site-specific hazard assessments (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 contemporary probabilistic methods, an 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 an additional two decades of data (i.e., magnitudes and hypocentres) relative to the 1991 assessments.

The NSHA18 (Allen et al., 2018b; 2020a) built upon the NSHM12 by better exploring the epistemic uncertainties in seismic source characterisation through the use of third-party source models and weighting these models using structured expert elicitation (Griffin et al., 2018; 2020). For the first time in Australia, a national fault-source model (FSM) was employed (Clark et al., 2016), together with an earthquake catalogue consistently expressed in terms of moment magnitude (Allen et al., 2018c). Neither the NSHM12 nor NSHA18 were accepted for use in the *AS1170.4* owing to concerns that: the models were based on limited earthquake data from low-seismicity regions; and some cities and regions would be exposed to unacceptable risks assuming the modern assessments of seismic hazard at an annual exceedance probability of 1/500 (Australian Earthquake Engineering Society, 2021).

A comparison of the Gaull et al. (1990), GSHAP (McCue, 1999), NSHM12 (Burbidge, 2012; Leonard et al., 2013), and NSHA18 (Allen et al., 2018b; 2020a) mean PGA hazard maps with a 10% probability of exceedance in 50 years using a consistent colour palette is shown in Figure 1.

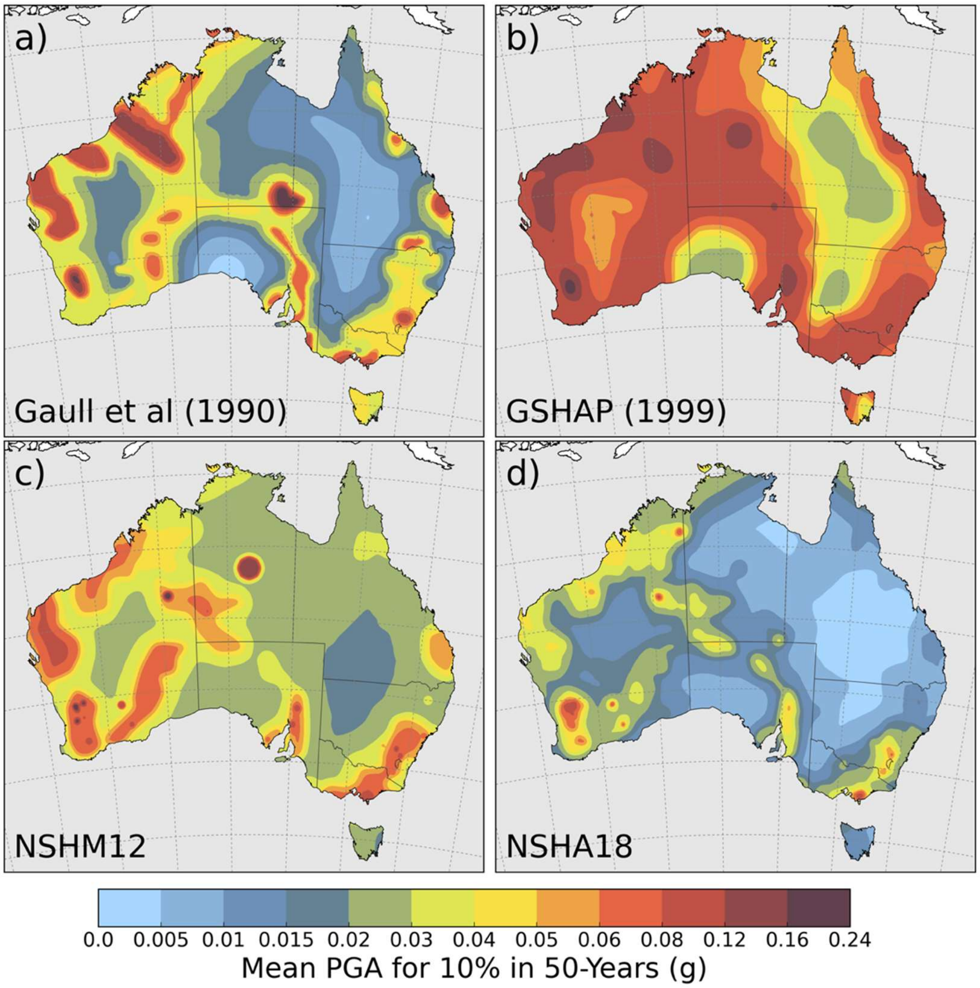

*Figure 1. Comparison of four generations of seismic hazard maps showing mean PGA for a 10% probability of exceedance in 50 years. Maps include: (a) Gaull et al. (1990); (b) the GSHAP (McCue, 1999); (c) the NSHM12 (Burbidge, 2012; Leonard et al., 2013), and; (d) the NSHA18 (Allen et al., 2018b).*

The maps in Figure 1 generally all show the same pattern of seismic hazard, but with the absolute values being quite different between the models. It is interesting to note that the NSHA18 is most consistent with the earliest model investigated (e.g., Gaull et al., 1990). However, the average level of hazard increased markedly from the Gaull et al. (1990) assessment to the McCue et al. (1993) assessment. As noted above, the contours of the latter map were based on expert opinion, and a number of conservative assumptions at the time of the development of this map led to the hazard increase. The decrease in hazard from the NSHM12 to the NSHA18 is, in part, due to the latter model's use of a catalogue uniformly expressed in terms of moment magnitude, $M_W$, which firstly decreases catalogue magnitudes for moderate sized events and secondly increases the Gutenberg-Richter *b*-value due to the non-linear relationship between local magnitude, $M_L$, and $M_W$ (Allen et al., 2018c; Allen et al., 2020a). A possible explanation for similarity of Gaull et al. (1990) and the NSHA18 is that each model was internally consistent with the magnitude type used for both the source-rate model and ground-motion characterisation model. For example, the Gaull et al. (1990) hazard model used $M_L$ to characterise both the source-rate and ground-motion models (GMMs), whereas, the NSHA18 used moment magnitude as is recommended for modern PSHAs (e.g., Baker et al., 2021; International Atomic Energy Agency, 2022).

## 3. Earthquake Catalogue Revision

Earthquake catalogues are fundamental inputs into any probabilistic seismic hazard assessment (PSHA) and are used to establish earthquake occurrence rates for a given source region or spatially varying smoothed seismicity model. The updated *National Seismic Hazard Assessment Earthquake Hypocentre Catalogue* (*NSHA23-Cat*) of historical earthquakes is the authoritative catalogue underpinning the NSHA23 (Allen et al., in press) and is used to determine earthquake rates for all area and gridded seismicity source models for continental Australia. The *NSHA23-Cat* combines multiple catalogues from national and international sources to provide the highest possible quality hypocentres and magnitudes for the assessment of earthquake hazard in Australia. The development of the catalogue uniformly expressed in terms of moment magnitude largely follows the same processes as were developed for the NSHA18 (Allen et al., 2018c). The key updates to the earthquake catalogue for the NSHA23 include the:

1. adjustment for local magnitudes, $M_L$, in recognition of improved knowledge of past observatory practice in Australia (Allen, 2021; Allen et al., in press);
2. improved consideration of the Wood-Anderson displacement seismometer (Anderson and Wood, 1925) calibration parameters used by Australian observatories over time, and compensation for these changes where necessary (Allen et al., in press);
3. recalculation of recent instrumental magnitudes (since 2010) with: improvements to the pre-processing of seismic waveforms; use of self-consistent Wood-Anderson calibrations, and; correction of known errors in instrument metadata that led to biases in catalogue magnitudes over several years (Cummins et al., 2021; Allen et al., in press);
4. update of magnitude conversions based on revised local magnitudes and an augmented dataset of moment magnitudes.

Together, the $M_L$ adjustments and the subsequent conversions to $M_W$ approximately reduce the number of earthquakes exceeding magnitude 5.0 by more than 50% in the *NSHA23-Cat* (Figure 2). This reduction in the number of moderate-to-large events is consistent with the *NSHA18-Cat* (Allen et al., 2018c) and recent studies to develop a homogenised "hazard ready" $M_W$ catalogue for the 2022 update to the New Zealand National Seismic Hazard Model (Christophersen et al., 2022).

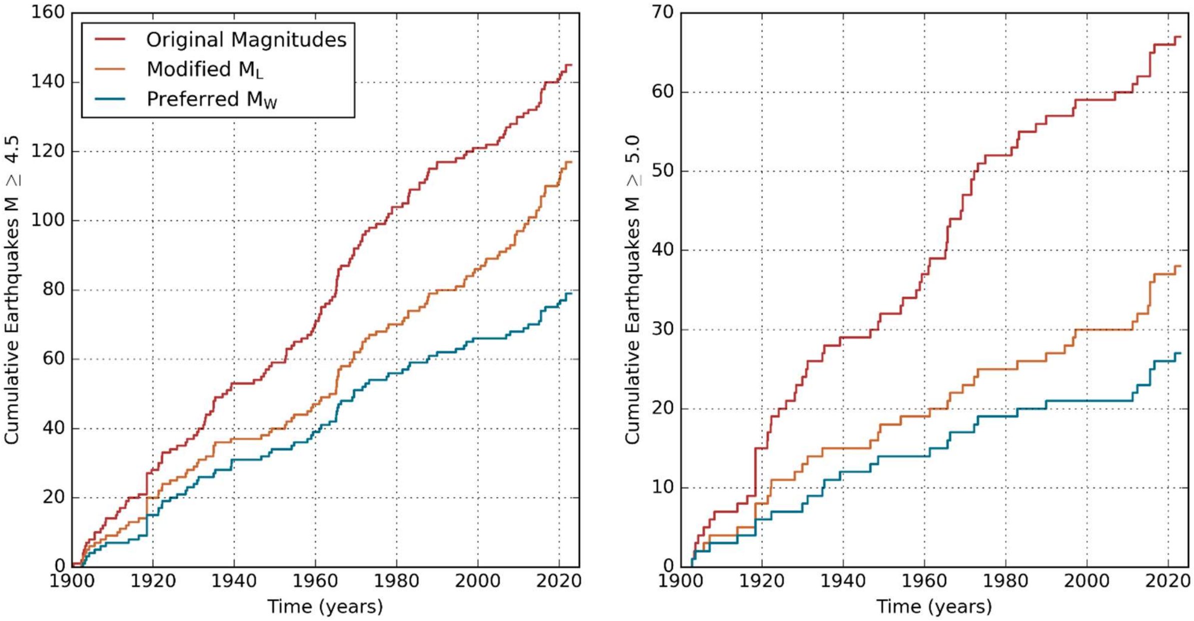

*Figure 2. Cumulative number of earthquakes exceeding magnitude (a) 4.5 and (b) 5.0 for since 1900 using the NSHA23 declustered catalogue (Allen et al., in press). The different curves show the original preferred magnitudes, preferred magnitudes with revised $M_L$, and preferred $M_W$. These figures are based on the non-declustered catalogue for earthquakes occurring in the South Australia and Eastern Australia magnitude zones (mapped in Allen, 2021).*

## 4. Catalogue Declustering

The *NSHA23-Cat* was declustered for use in magnitude-frequency distribution calculations using the Leonard (2008) time and distance windows. Based on the recommendations of Burbidge (2012), the declustering algorithm was modified to account for the long aftershock sequences proposed by Stein and Liu (2009) following large continental earthquakes. One difference between the NSHA18 and NSHA23 is the introduction of the notion of a "truncated declustering" time window. As recognised by many researchers (e.g., Leonard, 2008), the Australian continent possesses several examples where aftershock sequences may continue for decades following the original mainshock. For example, in 2019 a $M_W$ 5.0 earthquake occurred in the vicinity of the 1988 Tennant Creek (central Australia) earthquake sequence in the Northern Territory. Taking the classical declustering approach and the revised Leonard (2008) declustering algorithm, this 2019 event would be removed from the catalogue for the purposes of estimating seismic hazard. However, one could argue that new construction could occur in the region affected by the Tennant Creek, or other aftershock sequences, and that these "aftershocks" still pose a risk to new construction and the built environment. Consequently, the NSHA23 proposes an alternative method to decluster dependent earthquakes through the assignment of a truncated time window. This truncation window is intended to be a specific duration after which time, earthquakes that are associated with an enduring aftershock sequence may be treated as an independent event for the purposes of seismic hazard assessment. This is a pragmatic decision that is intended to re-introduce seismic moment into regions that may have been affected by large historical earthquakes, but where declustering effectively removes seismic moment from the seismic source models. This approach is not expected to have significant effects on the determination of earthquake rates for zone-based source models. However, it will affect the hazard forecasts for *smoothed seismicity* models. As an example, Figure 3 shows a comparison of the Risk Frontiers smoothed seismicity model (updated from Hall et al., 2007) applying "classical" declustering and "truncated" declustering approach with a 10-year truncation window. Minor variations in the resulting hazard are seen in the Southwest Seismic Zone of Western Australia, with more pronounced changes in the Tennant Creek region of the Northern Territory.

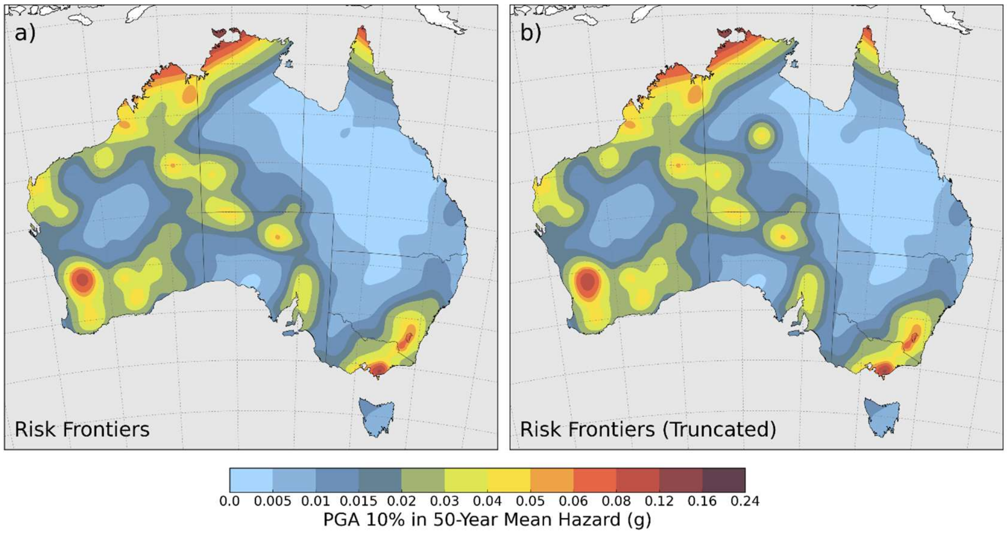

*Figure 3. Comparison of the mean PGA with a 10% chance of exceedance in 50 years for the Risk Frontiers smoothed seismicity model applying (a) the full (classical) declustering and (b) the truncated declustering approach with a maximum time window of 10 years. Minor variations in the resulting hazard are seen in the Southwest Seismic Zone of Western Australia and in the Tennant Creek region of the Northern Territory.*

## 5. Seismic-Source Characterisation Model (SSCM)

Seismic-source (or rate) models describe the annualised magnitude-frequency occurrence likely within a particular source zone, or spatially varying grid of point sources. The NSHA23 used a simplified suite of seismic source models (SSMs) relative to that used in the NSHA18 (Allen et al., 2018a). These SSMs were recalibrated with the updated *NSHA23-Cat*. Additionally, the relative weights of the SSMs were modified through the structured expert elicitation process (Griffin et al., 2023). As with the NSHA18 (Allen et al., 2018b), the NSHA23 considers five different seismic source-model classes. These include:

- *Background* area source zones that use broad geographic zones within which large earthquakes can occur anywhere with equal probability. These are models with 20 or fewer area-source zones at the scale of the Australian continent;
- *Regional* area source zones that assume the spatial distribution of seismicity is non-uniform at the scale of *background* source zones and that the distribution of historical seismicity is useful to forecast future earthquake occurrence. These are models with 30 or more area sources;
- *Smoothed seismicity* data-driven models that yield spatially-varying earthquake occurrence rates by smoothing the observed rates of earthquake occurrence with a given smoothing kernel (e.g., Frankel, 1995). These models assume that historical seismicity is a good predictor of future seismic hazard;
- *Seismotectonic* models combine *regional* zones with a *fault-source* model (FSM; Clark et al., 2016), and;
- *Smoothed seismicity* models combined with a *FSM*.

The latter two source-model types represent minor variations on the *regional* and *smoothed seismicity* models, respectively. The NSHA18 documentation describes these source model types in more detail (Allen et al., 2018a; Allen et al., 2018b).

Whilst the modelled slip-rates on known Australian faults would be considered low by global standards, these sources can still affect seismic hazard forecasts at low exceedance probabilities (Clark and Allen, 2018). The difference between the 2018 FSM and 2023 FSM includes parameterisation changes to a moderate number of features, modification of fault geometries for a few existing features, and the addition of a small number of new features. Updates of the FSM leads to increased seismic moment contribution from the neotectonic features in the: Adelaide, South Australia region; southeastern Australia, and; the Northwest Shelf (Clark, 2023).

The approach for characterising the remaining source model types in the NSHA23—including *background regional* and *smoothed seismicity* model types—remained consistent with the approach taken in the NSHA18 (Allen et al., 2018b). For the area-source model types, the source geometries adopted for the NSHA23 were the same that were used in the NSHA18. The primary difference is that the earthquake rates were re-characterised using the *NSHA23-Cat*. Additionally, the seismic-source characterisation model (SSCM) was simplified slightly by setting the class weight of the *regional* and *smoothed seismicity* models to zero given their low weights assigned through the expert elicitation process (Griffin et al., 2023) and reassigning these weights to the *seismotectonic and smoothed seismicity (with FSM)* model classes, respectively. To rectify some model artefacts, the *smoothed seismicity (with FSM)* models were classified into to two model sub-classes: fixed kernel and adaptive kernel smoothing. This was done to effectively down-weight adaptive *smoothed seismicity* models that result in high hazard peaks in regions with high earthquake rates without a clear main shock for declustering purposes (e.g., near Kalgoorlie, Western Australia).

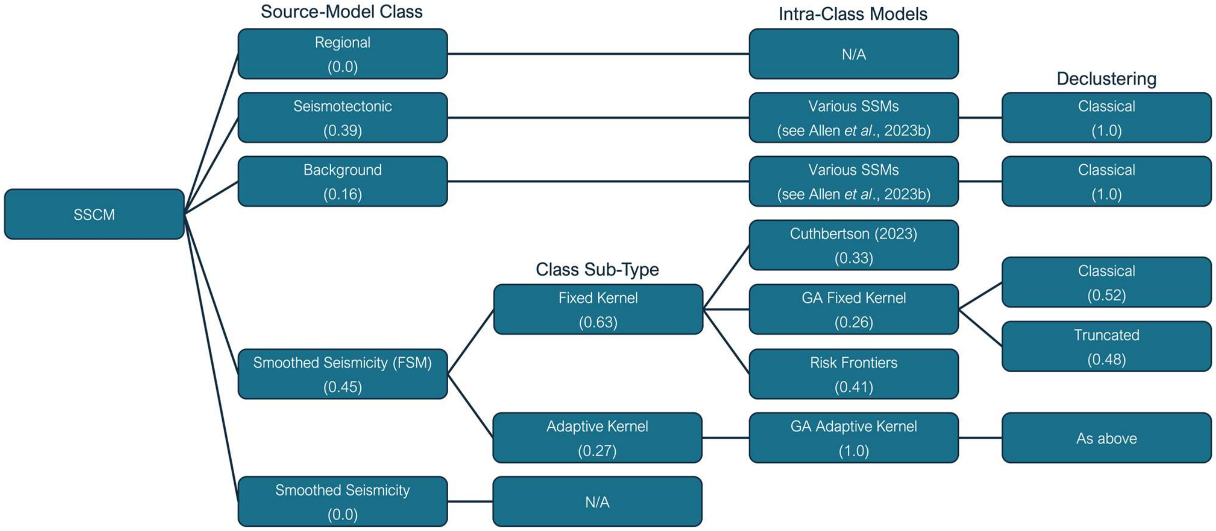

*Figure 4. Simplified SSCM assigning weights from the smoothed seismicity to the smoothed seismicity with faults source model classes.*

## 6. Ground-Motion Characterisation Model (GMCM)

Using the updated and extended suite of ground-motion data from small-to-moderate-magnitude Australian earthquakes (Ghasemi and Allen, 2021; 2023), the performance of candidate GMMs was evaluated for their use in the Australian context. Residual analysis of these datasets was undertaken and the results were shared during the expert elicitation workshop (Allen et al., 2023b). The expert elicitation workshop led to the update of the GMM logic trees for the *cratonic*, *non-cratonic* and *subduction* tectonic region types as defined in (Allen et al., 2018b). The final GMCM weights from the expert elicitation are shown in Table 1. In terms of the GMM set for the *subduction* tectonic region type, one of the more significant changes was the high weight given to the new far-field GMM developed specifically for earthquakes occurring in the Banda Sea affecting northern Australian sites (Allen, 2022).

## 7. NSHA23 Hazard Results

Figure 5a shows the mean PGA (in g) for 10% probability of exceedance in 50-years national-scale seismic hazard map calculated for *AS1170.4* Site Class $B_e$ (equivalent to $V_{S30}$ = 760 m/s). In any updated hazard seismic assessment, it is important to understand the rationale for any changes in the estimated hazard relative to previous models. To explore this, we can decouple the component parts of the hazard model in several ways. In the Figure 6, we plot the mean hazard curves for both the NSHA18 and NSHA23 for selected Australian capital cities. In addition, two variants to the model are considered: firstly, the NSHA23 SSCM with the NSHA18 GMCM, and secondly, the NSHA18 SSCM with the NSHA23 GMCM. The former comparison explores the change in hazard due to the change of the GMMs considered relative to the mean NSHA23 hazard curves, and the latter explores the change in mean hazard due to changes in the SSCM. Any changes in the SSCM will largely be due to changes in the relative weights of the source-model classes, together with magnitude adjustments in the *NSHA23-Cat*. Minor contributions due to updates in the FSM at lower probabilities of exceedance may also exist.

*Table 1. Final ground-motion model weights applied in NSHA23.*

| **Model Name*** | **Tectonic Region Type** | **Intra-Region Weight** | **Reference** | **Integration Distance** |
|---|---|---|---|---|
| Allen2012_SS14 | Non-cratonic, Extended, Oceanic and Active Crust | 0.3 | Allen (2012) | 400 km |
| AtkinsonBoore2006 | | 0.15 | Atkinson and Boore (2006) | |
| DrouetBrazil2015 | | 0.19 | Drouet (2015) | |
| SomervilleEtAl2009NonCratonic | | 0.36 | Somerville et al. (2009) | |
| NGAEastGMPE | | | Goulet et al. (2017) | |
| Allen2012_SS14 | Cratonic | 0.24 | Allen (2012) | 400 km |
| AtkinsonBoore2006 | | 0.13 | Atkinson and Boore (2006) | |
| DrouetBrazil2015 | | 0.14 | Drouet (2015) | |
| ESHM20Craton | | 0.1 | Weatherill et al. (2020) | |
| NGAEastGMPE | | 0.09 | Goulet et al. (2017) | |
| SomervilleEtAl2009YilgarnCraton | | 0.16 | Somerville et al. (2009) | |
| SomervilleEtAl2009NonCratonic | | 0.14 | Somerville et al. (2009) | |
| Allen2022 | Subduction | 0.81 | Allen (2022) | 1000 km |
| AtkinsonBoore2006 | | 0.1 | Atkinson and Boore (2006) | |
| NGAEastGMPE | | 0.09 | Goulet et al. (2017) | |

* Model name as defined in the *OpenQuake-engine gsim* library (Pagani et al., 2014).

In general, there are minor changes in the mean PGA hazard (mostly decreases) relative to the NSHA18 due to the NSHA23 SSCM. However, these decreases due to the SSCM are more than offset due to changes in the GMCM, resulting in a net increase in hazard over the range of exceedance probabilities considered. The most significant changes in hazard occurred in the City of Darwin, Northern Territory. This change in hazard is almost exclusively due to the use of the Allen (2022) GMM, which forecasts significantly higher short-period ground motions than the GMMs which contributed to the NSHA18 GMCM for that region. Considering all localities, the mean percentage increase for the NSHA23 relative to the NSHA18 for mean PGA at the 10% chance of exceedance in 50 years is 25.8% ± 33.5%. Whilst this may seem like a rather significant change, when the hazard difference is considered across all sites, the mean difference in PGA hazard is only 0.008 ± 0.011 g.

Finally, the ratio of the NSHA23 relative to the NSHA18 for the mean PGA with a 10% probability of exceedance in 50 years is mapped in Figure 5b. This map shows an almost uniform increase in the seismic hazard in the NSHA23 relative to the NSHA18 on a spatial scale, but generally a with ratios near 1.0. Most of the relatively modest changes are a result of changes to the GMCM. The largest changes in hazard occur in northern Australia due to the use of the new Allen (2022) GMM developed for earthquakes occurring in the Banda Sea that affect sites in Australia. The “bullseye” in the hazard ratio near Tennant Creek, Northern Territory, occurs due to adjustments in the declustering approach that result in fewer earthquakes being declustered from the *NSHA23-Cat* for the purposes of *smoothed seismicity* model development (Figure 3).

For the first time, the NSHA23 calculates hazard on different site classes, assuming varying time-averaged shear-wave velocities in the upper 30 m of the crust (i.e., $V_{S30}$): 150, 270, 450, 760 and 1,100 m/s (Allen et al., 2023b). It is important to note that many localities across Australia lie within sedimentary basins and sites may be subject to significant ground-motion amplification owing to basin resonance effects. Whilst the calculation of hazard for different site conditions is a significant advance, there is no explicit modelling of basin resonance.

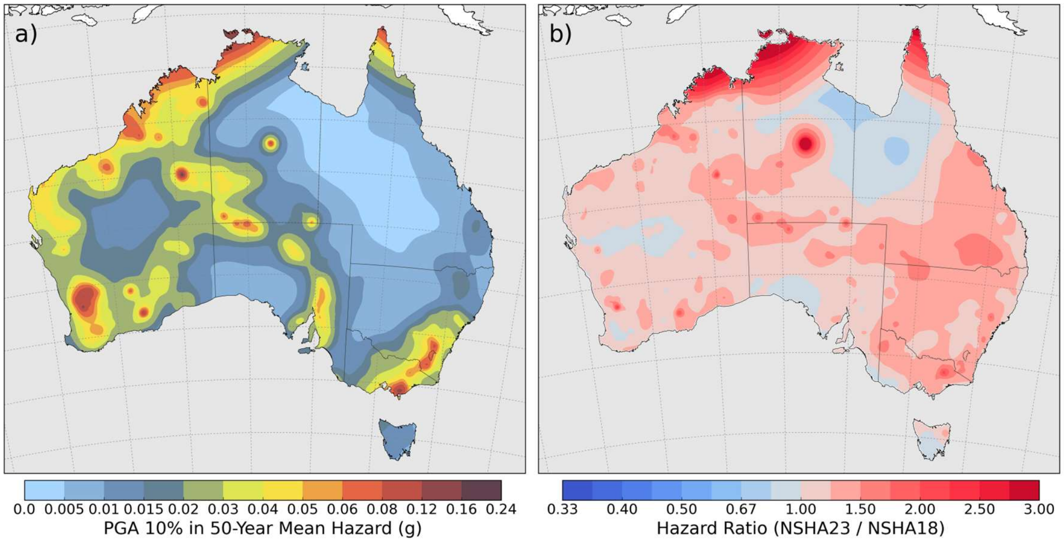

*Figure 5. a) NSHA23 map indicating the mean PGA (in g) for 10% probability of exceedance in 50-years on AS1170.4 Site Class $B_e$ (equivalent to $V_{S30}$ = 760 m/s). b) Map showing the ratio of the NSHA23 relative to the NSHA18 for the mean PGA on AS1170.4 Site Class $B_e$ with a 10% probability of exceedance in 50 years.*

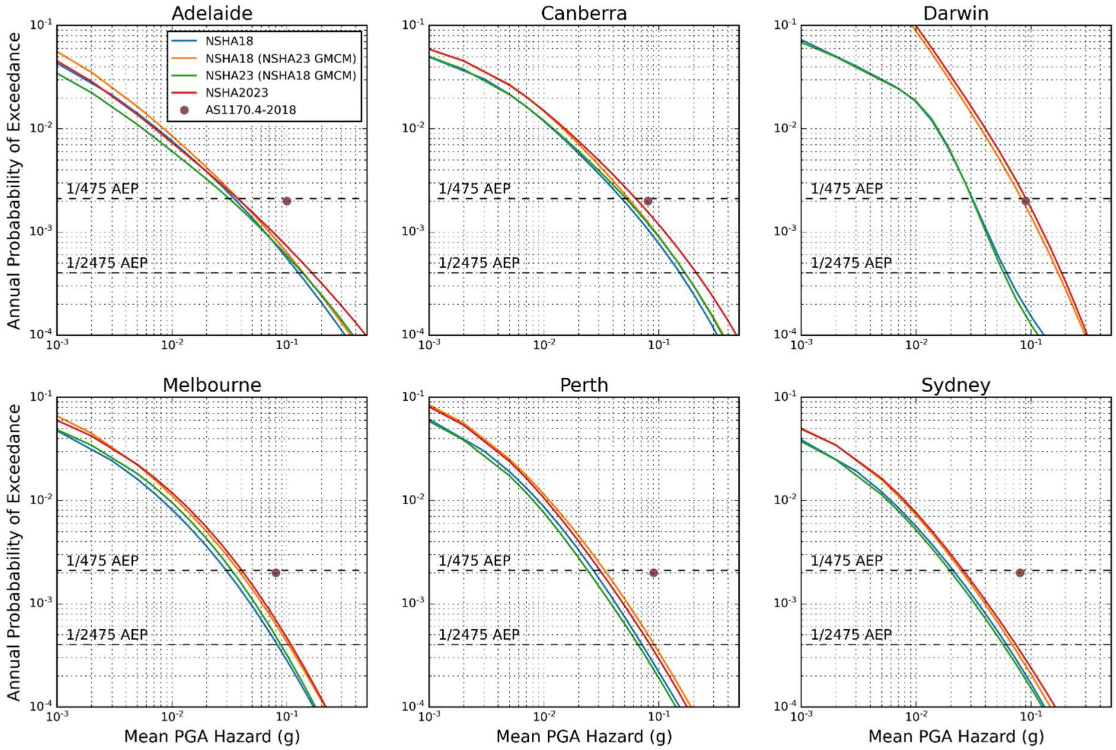

*Figure 6. Mean hazard curve comparisons for capital cities for PGA on AS1170.4 Site Class $B_e$ ($V_{S30}$ = 760 m/s) showing the: NSHA18; NSHA18 SSCM with the NSHA23 GMCM; NSHA23 SSCM with the NSHA18 GMCM; and NSHA23.*

## 8. Conclusions

Geoscience Australia, together with contributions from the broader Australian seismological community, has updated its national seismic hazard assessment to ensure it incorporates best practice and evidence-based science. The NSHA23 has used the NSHA18 as a foundation and has built upon the previous assessment through several key updates and revisions to model components. At a high level, these include updates to the earthquake catalogue and fault-source model, together with review and revision of the SSCM and GMCM logic trees. The update of these model components has led to changes in seismic hazard estimates that are spatially variable across the nation.

In general, there are minor changes in the hazard (mostly decreases) due to the NSHA23 SSCM. However, these decreases due to the SSCM are offset due to changes in the GMCM, resulting in a net increase in hazard over the range of exceedance probabilities. The significant changes in hazard to the City of Darwin are almost exclusively due to the use of the Allen (2022) GMM, which forecasts significantly higher ground motions than the GMMs which contributed to the NSHA18 GMCM.

The NSHA23 provides estimates of seismic hazard for the six Australian states and two mainland territories. However, it does not provide updated hazard factors for Australia's Antarctic and other offshore territories (e.g., Christmas Island, Cocos Island, Heard Island, Lord Howe Island, Macquarie Island and Norfolk Island). Quantifying the seismic hazards for these localities will be the focus of future work.

Finally, the underlying data used to inform this update has improved since the 2018 assessment, as has our confidence in key modelling decisions (e.g., magnitude adjustments and conversions). The epistemic uncertainty has been extensively sampled through the inclusion of 15 seismic source models, contributed by Geoscience Australia and third-party sources. Consequently, the updated NSHA23 provides an improved understanding of seismic hazard and its uncertainties for Australia and forms a basis for improving earthquake resilience for Australian communities. At the time of writing, Geoscience Australia continues to work with Standards Australia's BD-006-11 sub-committee to adjust outputs from the NSHA23 for input to the AS1170.4.

## 9. Acknowledgements

The NSHA23 draws together an abundance of this information to build the national hazard model. We particularly thank our third-party source model contributors for sharing their work and donating their time through various NSHA23 workshops and discussions. In particular, we thank the contributors of the third-party smoothed seismicity models (Russell Cuthbertson [Seismology Research Centre], Jacob Evans and Paul Somerville [Risk Frontiers]), which required an iterative model development and implementation with the NSHA23 team after finalisation of the *NSHA23-Cat*. We are grateful to the participants and experts of the SSCM and GMCM Expert Elicitation workshops listed in Allen et al. (2023b) for their valuable contributions to the NSHA23 development. We are particularly grateful to the NSHA23 external peer review panel–Julian Bommer, Matt Gerstenberger, Nico Luco, Marco Pagani and Mark Stirling–for their guidance and advice through the development of the NSHA23. The authors acknowledge the traditional owners and custodians of Country throughout Australia and acknowledge their continuing connection to land, waters and community. We pay our respects to the people, the cultures and the elders past and present. Finally, the authors publish with the permission of the CEO of Geoscience Australia.

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