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# REFLECTIONS ON THE NSHA18: RETHINKING FUTURE SEISMIC HAZARD ASSESSMENTS FOR AUSTRALIA

T. I. Allen(1), J. D. Griffin(2), J. S. Stephenson(3), D. J. Clark(4), H. Ghasemi(5)

(1) *Seismologist, Place, Space & Communities Division, Geoscience Australia, trevor.allen@ga.gov.au*
(2) *Earthquake Hazard Scientist, Department of Geology, University of Otago, jonathan.griffin@postgrad.otago.ac.nz*
(3) *Seismologist, Place, Space & Communities Division, Geoscience Australia, joanne.stephenson@ga.gov.au*
(4) *Earthquake Geologist, Place, Space & Communities Division, Geoscience Australia, dan.clark@ga.gov.au*
(5) *Seismologist, Place, Space & Communities Division, Geoscience Australia, hadi.ghasemi@ga.gov.au*

## *Abstract*

An updated National Seismic Hazard Assessment of Australia was released in 2018 (the NSHA18). This assessment leveraged off advances in earthquake-hazard science in Australia and analogue tectonic regions to offer many improvements over its predecessors. The outcomes of the assessment represent a significant shift in the way national-scale seismic hazard is modelled in Australia, and so challenge long-held notions of seismic hazard amongst the Australian seismological and earthquake engineering community. The NSHA18 is one of the most complex national-scale seismic hazard assessments conducted to date, comprising 19 independent seismic source models (provided by Geoscience Australia and third-party contributors) with three tectonic region types, each represented by at least six ground motion models. The NSHA18 applied a classical probabilistic seismic hazard analysis (PSHA) using a weighted logic tree approach, where the model weights were determined through two structured expert elicitation workshops.

Since the model's completion, Geoscience Australia has been able to reflect on the choices made both through the expert elicitation process and through decisions made by the NSHA18 team. 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; 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 *b*-values determined from broad neotectonic domains, and; 5) the characterisation and assignment of ground-motion models used for different tectonic regimes. This paper discusses lessons learned through the development of the NSHA18, identifies successes in the expert elicitation and modelling processes, and explores some of the abovementioned challenges that could be reviewed for future editions of the model.

*Keywords: seismic hazard, neotectonic faults, source model, ground-motion model, NSHA18*

## 1. Introduction

In 2018, Geoscience Australia, together with contributors from the wider Australian seismology community, produced a revised National Seismic Hazard Assessment [NSHA18; 1]. The NSHA18 leverages advances in earthquake-hazard science in Australia and analogue tectonic regions over the last three decades to offer many improvements over its predecessors, including: calculation in a fully probabilistic framework using the OpenQuake-engine [2]; incorporation of almost three decades of new, high-quality earthquake epicentre data [3]; consistent expression of earthquake magnitudes in terms of moment magnitude, $M_W$ [3]; inclusion of a national fault-source model based on the Australian Neotectonic Features Database [4]; and, the estimation of epistemic (i.e., modelling) uncertainty through the use of multiple alternative seismic-source models (SSMs) and ground-motion models (GMMs) combined with structured expert elicitation [5]. The NSHA18 is the most complete data publication of any Australian national seismic hazard assessment – inputs and outputs are openly available, discoverable and accessible to end-users (see Allen *et al.* [1] for details).

Calculated peak ground acceleration (PGA) values at the 10% probability of exceedance in 50 years (Fig. 1) across Australia have decreased, on average, by 72% relative to the earthquake hazard factors published for localities in the Australian earthquake loading code, the *AS1170.4–2007* [6]. The *AS1170.4* was recently amended by Standards Australia's BD–06–11 Technical Subcommittee [7]. Given the reduction in seismic hazard estimates in the NSHA18, the amended *AS1170.4–2007 (R2018)* retains seismic demands developed in the early 1990s [8] and introduces a minimum hazard design factor of $Z = 0.08$ g to address concerns that lesser hazard factors at the 1/500 annual exceedance probability may not assure life safety throughout the Australian continent. Allen [9] discusses the NSHA18 results in the context of whether provisions in the existing *AS1170.4* are appropriate for the design and construction of structures in low-seismicity environments. In contrast, this paper reflects on the process used to undertake source and ground-motion characterisation for the NSHA18 and identifies potential improvements to processes and scientific methods to advance the characterisation of seismic hazard for Australia in the future.

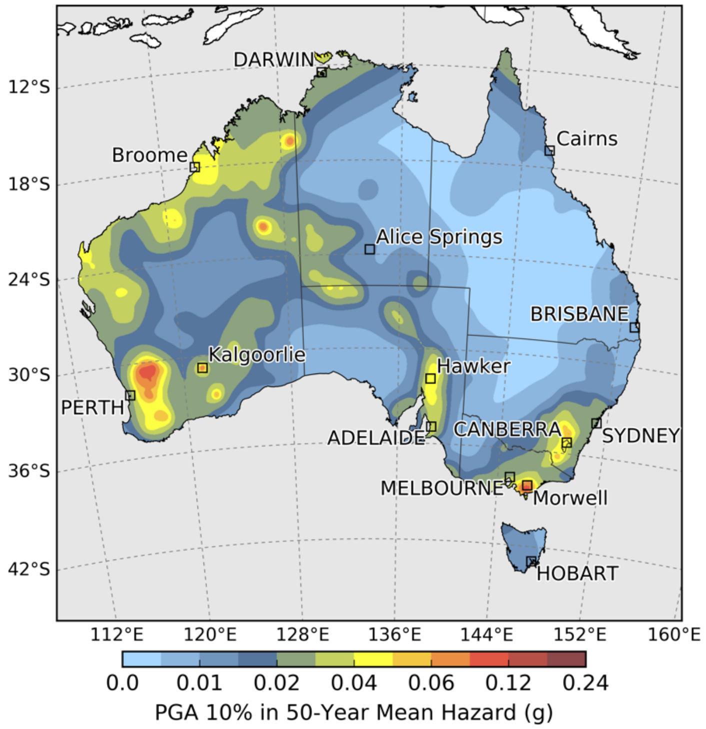

Fig. 1 – 2018 National Seismic Hazard Assessment of Australia (NSHA18) showing peak ground acceleration (PGA) with a 10% in 50-year probability of exceedance (PoE) on site class $B_e$ [1]. Site class $B_e$ is now defined as equivalent to a time averaged shear-wave velocity in the upper 30 m ($V_{S30}$) of 760 m/s.

## 2. Reflections on the NSHA18

With the completion of the NSHA18 [1, 10], it is timely to pause and reflect on the successes and limitations of this model update. The NSHA18 took many different approaches to its predecessors to deliver an updated national-scale seismic hazard assessment for Australia; from the expert elicitation workshops to characterise and weight the model inputs, to the use of a homogenised earthquake catalogue defined in $M_W$. These changes have had consequences for the final hazard estimates, and it is important that we are able to understand and articulate the consequences of the choices made, both by the Geoscience Australia development team and through the expert elicitation workshops. Boundaries between what was scientifically reducible and what remained epistemologically uncertain remained contested [11]. This was one of the factors, amongst others, which affected the acceptance and use of the NSHA18 within the *AS1170.4*. Herein, we summarise some of the key changes of the seismic hazard model from previous iterations and discusses the impact of these changes.

### 2.1 Expert Elicitation Workshops

Seismic hazard assessments are inherently uncertain due to the long return periods of damaging earthquakes relative to the time period of human observation, particularly for stable continental regions (SCRs). Consequently, there can often be multiple, scientifically defensible, alternative approaches for modelling this hazard. Expert elicitation [12, 13] is a process that is often drawn upon to quantify the relative probabilities of alternative models, sampling the epistemic uncertainty to approximate the "true" model. Geoscience Australia adopted expert elicitation to characterise the seismic-source characterisation (SSCM) and ground-motion characterisation model (GMCM) for the NSHA18. Seventeen experts in seismic hazard assessment, representative of the collective expertise of the Australian earthquake hazard community, were invited to two workshops held at Geoscience Australia [5]. At these workshops, the experts each assigned weights to alternative models representing their degree of belief that a particular model is the true model. The experts were calibrated through a series of questions that tested their knowledge of the subject matter and ability to assess the limits to their knowledge [5] and this calibration was used to weight the contributions of a given expert.

The SSCM workshop not only provided weightings to the individual SSMs, but also provided guidance on the parameterisation for each model, such as the maximum magnitude, the magnitude-frequency distribution (MFD) type for fault-sources [e.g., 14, 15], and selection of processes to assign Gutenberg-Richter [14] *b*-values to seismic sources. The parameterisation of seismic-source model MFDs was based on a single earthquake catalogue with homogenised magnitudes [3]. A limitation of the NSHA18 implementation was that not all experts agreed on the boundary between what was epistemically uncertain and what was scientifically reducible [11]. This is particularly true of the work undertaken independently from the expert elicitation with respect to the catalogue. With the benefit of hindsight, whilst extensive in nature, it was clear that the SSCM expert elicitation questions were not exhaustive. These are lessons that can be drawn upon for future national assessments.

Nevertheless, the NSHA18 process attempted to accept and implement the outcomes of the expert elicitation workshops [5] as closely as practically possible. The Geoscience Australia hazard team has reflected on the choices made through the expert elicitation process and the consequences of those choices on the production of the final seismic hazard model, such as the relative weights of different source-model "classes" or ground-motion models [10]. These impacts were not fully appreciated prior to embarking in the development of the NSHA18 nor were they evident at the time of the expert elicitation workshops. It is thus recommended that for future national-scale hazard assessments, the experts be re-engaged to allow for 360-degree feedback and to review the consequences of choices made during the expert elicitation process. The primary limitation to this approach, however, is that the experts may prejudice their responses to achieve specific outcomes; these limitations should be mitigated by ensuring the expert re-engagement process is be carefully structured and transparent [11].

### 2.2 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. Multiple SSMs combined through a weighted logic-tree approach are often used in probabilistic seismic hazard assessments (PSHAs) to capture the epistemic uncertainty in seismic-source modelling [e.g., 16, 17]. The calculated ground-motion hazard can be very sensitive to the location of classical area-source-model boundaries [18], which is often subjective and can be dependent on a modeller's professional judgment. Greater consideration of epistemic uncertainty in modelling seismic sources was incorporated in the NSHA18 through a call for third party source models [19]. In total, the NSHA18 used 19 independent SSMs for estimating the rates of earthquake occurrence at any given location in continental Australia [1]. The diversity of contributed SSMs demonstrates the epistemic uncertainty that exists with regards to how best to characterize intraplate seismicity. The source models were weighted through structured expert elicitation [5] and each model provides a unique spatial representation of modelled earthquake occurrence.

In the NSHA18, five SSM "classes" were defined [1]. These include:

- *Background* area source zones that use broad geographic zones within which large earthquakes can occur anywhere with equal probability. These are typically models with 20 or fewer area-source zones on the national scale;
- *Regional* area source zones are smaller in size and assume the spatial distribution of seismicity is non-uniform at the scale of *background* source zones. These are typically models with 30 or more area sources on the national scale;
- *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., 20]. These models assume that historical seismicity is a good predictor of future seismic hazard;
- *Seismotectonic* models (e.g., *regional* zones combined with a *fault-source* model) [4], and;
- *Smoothed seismicity* combined with a *fault-source* model.

The latter two source-model classes that include a *fault-source* model represent minor variations on the *regional* and *smoothed seismicity* models, respectively. The NSHA18's *fault-source* model included 356 onshore faults and 23 offshore faults, modelled as simplified planes, assigned with a general dip and rake direction [4].

Whilst the NSHA18 process was successful in soliciting contributions from the wider seismological community and thus sampling the source-model uncertainty, it made the model challenging to implement and run, even on modern high-performance computing infrastructure. Leonard [21] and Allen *et al.* [10] explored the variability in seismic hazard amongst the independent source-model contributions. Both assessments found that, for a range of localities, the estimated ground-motion hazard tended to cluster for SSMs within a given class. This suggests, that future SSCMs may be simplified to achieve similar mean hazard estimates while significantly streamlining the model run times. In contrast, this may risk a potential loss of inclusiveness and consequently, the acceptance of the outputs amongst the community.

### 2.3 Identification and Characterisation of Active Faults

The use of a national fault-source model [NFSM; 4] represented a significant advance for seismic hazard modelling in Australia. Unique challenges are faced in modelling the seismic hazard from active (or neotectonic) faults in intraplate regions. Low fault slip-rates relative to landscape modification rates often lead to poor discoverability of fault sources, and can result in incomplete characterisation of rupture behaviour [e.g., 22, 23]. However, regional and local assessments have demonstrated that fault sources assigned with activity rates consistent with paleoseismic observations can significantly impact on PSHAs in Australia [e.g., 22, 24], particularly for lower exceedance probabilities where there may be several fault sources that contribute to the total seismic hazard at a site.

Incompleteness of the neotectonic fault record might be expected to result in an under-estimate of the hazard, especially in regions where landscape modification rates are comparable to, or exceed the rates of tectonic relief building [22, 25]. However, the incompleteness in the fault record might be counterbalanced by the knowledge that faults with lower slip rates and thus, low potential of discovery, are not expected to contribute significantly to ground-motion hazard for exceedance probabilities that may affect ordinary-use structures (e.g., 10% or 2% probability of exceedance in 50 years) [e.g., 23, 26]. These are significant challenges that face seismic hazard modellers in SCRs. However, new, openly-available high-resolution topographic datasets (e.g., elevation.fsdf.org.au/) are now becoming available across much of the continent. These data, combined with dedicated field investigations could enable improved discoverability and characterisation of neotectonic faults across Australia. Furthermore, studies investigating the potential for spatial and temporal clustering behaviour among faults will improve our ability to capture the epistemic uncertainty of earthquake ruptures on known faults across the continent [e.g., 27] and in tectonically analogous regions [e.g., 28].

### 2.4 Catalogue – Magnitude Adjustments

Modern PSHAs rely on earthquake catalogues consistently expressed in terms of moment magnitude, $M_W$. Moment magnitude is commonly considered to be the best representation of an earthquake's size [i.e., 29]. Furthermore, the use of heterogeneous magnitude types for the estimation of Gutenberg-Richter recurrence statistics will lead to a discrepancy between the occurrence rates of earthquakes of a given magnitude and the ground-motions assigned to those earthquakes in the hazard calculation. Unfortunately, $M_W$ is not routinely calculated for small-magnitude local events by many national networks, including the Australian national network. For use in earthquake recurrence calculations [i.e., 14], magnitude conversion equations are often applied to convert local magnitude ($M_L$) to $M_W$. Unless these conversions are time-dependent, they commonly assume that $M_L$ estimation has been consistent for the observation period. For earthquakes in Australia, there is a need to correct pre-1990 magnitude estimates to ensure continuity with current observatory magnitude estimation methods [3]. Failing to undertake this correction for magnitudes listed in the Australian earthquake catalogue leads to differences of 0.5 magnitude units or more due to the historical use of inappropriate magnitude formulae [e.g., 30]. Ideally, these corrections could be achieved using original amplitude and period picks. However, this presently cannot be easily achieved for pre-digital (and even some early-digital) data. Allen *et al.* [10] and Griffin *et al.* [11] explore the impact of the aforementioned adjustments to catalogue magnitudes on overall hazard. These studies show that the combined effects of $M_L$ adjustments and $M_W$ conversions are significant, and generally contribute to reductions in hazard by factors of generally two or less on a national scale.

The development of the earthquake catalogue, including magnitude revision and homogenisation, was one of the most controversial aspects of the NSHA18 amongst the domestic Australian seismological community [3]. Additional, the catalogue adjustments led to more significant changes to hazard levels than the weighting of alternative source models [11]. While this was generally viewed as a scientific advance, in that a significant systematic error of historic magnitude estimation was removed, some maintained the alternate view that the new catalogue is just one of multiple alternative catalogues that contribute to the epistemic uncertainty. The criticisms aimed at the NSHA18 approach to the catalogue demonstrate that the boundaries between epistemic uncertainty and settled science can be contested [11]. In the case of the catalogue revisions, the updated and homogenised catalogue had not yet been published through traditional peer-review mechanisms at the time of the expert workshops. It is recommended for future hazard assessments that early engagement with the expert community should aim to identify key epistemic problems, and agree on a framework for defining which problems are scientifically reducible to a single model within the timeframes of the hazard assessment, and which should be treated through alternative logic tree branches [11].

### 2.5 Catalogue – Declustering

Following large historical earthquakes in Australia, it is common to experience very active and prolonged sequences of aftershocks [31, 32]. These aftershocks can introduce biases into fitting Gutenberg-Richter [14] magnitude-frequency distributions (MFDs) for independent earthquakes in regional datasets. The catalogue declustering was undertaken using the methods described in Allen *et al.* [3]. Given the characteristics of aftershock sequences from Australian earthquakes, Geoscience Australia chose to follow the globally accepted practice to decluster the catalogue [e.g., 33]. Some workshop participants argued that foreshocks and aftershocks still contribute to the total seismic moment rate, and therefore should be considered in calculating recurrence rates for larger earthquakes, even if this violates the classical Poisson assumption. The results from the expert elicitation yielded a non-preferred, yet significant, weight to the use of a non-declustered earthquake catalogue [5].

Relative to other seismic hazard assessments for Australia [e.g., 34] the use of the declustering model used by Allen *et al.* [3] significantly reduces the hazard in regions such as Tennant Creek in central

Australia; a region which has seen ongoing aftershocks following the 1988 earthquake sequence [35]. Declustering effectively reduces this region to one earthquake; the $M_W$ 6.6 mainshock on 22nd January 1988. However, one may consider the two large Tennant Creek foreshocks as being independent earthquakes that occurred on separate fault segments [e.g., 36]. Consequently, arguments for their inclusion in the source model development could be made.

Given that aftershocks are still occurring (including a $M_W$ 5.0 event in August 2019), well after the Tennant Creek earthquake sequence commenced with a $M_L$ 4.1 foreshock in 1986 [35], it is reasonable to ask if this region be should be effectively reduced to one earthquake for the purposes of PSHA? This is a question that provokes significant debate among seismologists and one that is difficult to address through modern PSHA methodology [e.g., 37]. Whilst the Tennant Creek sequence has been reduced to one earthquake, the NSHA18 also considers the Tennant Creek rupture as an active fault source [4]. Given that there was no tectonic relief across the Tennant Creek Scarp prior to its causative events [23], the regional erosion rates of less than 5 m/Myr [38] effectively provide maximum bounds for long-term slip rates on the Tennant Creek fault sources. A caveat to consider is that scarps in central and western Australia that have been studied in detail [such as the Tennant Creek scarps; 36], either show no evidence for recurrence, or evidence for very limited recurrence of large events (i.e., less than 3-4 events in the last 100 kyr, with potential for previous events at times unspecified).

### 2.6 Seismic-Source Characterisation – Rate Definition

Another aspect of the NSHA18 that was not universally accepted was the approach used to characterise earthquake rates within seismic source models. Some source-model developers provided rate models together with zone-based or gridded seismicity models based on their own catalogues [e.g., 39, 40]. Others did not explicitly provide these parameters, but argued for the use of a Gutenberg-Richter *b*-value of 1.0 [e.g., 41]. Given the limitations associated with running a national-scale model and accommodating the various permutations suggested for estimating earthquake rates for the 19 considered source models, a single approach was taken to characterise the seismic rate calculations for each SSM using both a consistent catalogue [3] and a consistent method for estimating the *b*-value [5]. In the case of gridded *smoothed seismicity* models, the Geoscience Australia team worked together with the source-model developers to update their model contributions with the final NSHA18 catalogue.

### 2.7 GMM characterization

Ground-motion models (GMMs) form an essential component to modern PSHAs and are often considered to contribute some of the largest uncertainties in seismic hazard assessments [42]. The GMCM for the NSHA18 was developed through the expert elicitation workshops and characterised three unique tectonic region types: *cratonic*, *non-cratonic*, and *subduction*. Together with their existing perspectives and experience, Geoscience Australia provided expert elicitation participants with quantitative assessments of the performance of a suite of ground-motion models [43] from which the participants were able to guide their model selections and weightings. While data from moderate-to-large earthquakes in SCR settings is sparse, it is acknowledged that there are some key data from significant Australian earthquakes that were not integrated into these quantitative assessments. Consequently, whilst it was still representative, the development of the GMCM was calibrated from incomplete information. Furthermore, aside from a few event-specific examples, the GMCM for the *subduction* tectonic region type was based on limited evidence. Ground motions from the latter tectonic region type dominates hazard for northern Australia and remains subject to considerable uncertainty [9].

## 3. Looking Forward – Opportunities for Improvement

The focus over the coming model update cycle is to identify and fill key knowledge gaps that were either known limitations prior to the commencement of the NSHA18, or recognised through the NSHA18 process. Three key themes are identified: 1) ongoing improvements to the earthquake catalogue; 2) rethinking the

NSHA18 strategy for calculating earthquake occurrence rates, and; 3) improvements in ground-motion datasets for quantifying GMM performance and the update and development of Australian-specific models. Not explicitly discussed below, but summarised in Section 2.3, is the ongoing need for improved identification and characterisation of potentially active faults that could pose significant ground-motion hazard to communities and infrastructure, particularly at low probabilities of exceedance.

### 3.1 Improvements to the Earthquake Catalogue

As discussed in Section 2.4, one of the most controversial aspects of the NSHA18 was the development of the earthquake catalogue, including magnitude revision and homogenisation [3, 11]. The need to homogenise the earthquake magnitudes to a consistent magnitude type was vigorously debated. The decision by Geoscience Australia to adopt a catalogue consistently expressed in $M_W$ was independent from the expert elicitation workshops and was based on current best practise. Nevertheless, the data on which the magnitude-conversion equations were based were limited [3, 44]. These equations should be reviewed and revised with new data for future hazard studies.

Another criticism of the NSHA18 is that it largely ignored pre-instrumental data [e.g., 45]. Strict magnitude-completeness models were adopted to calculate MFDs for the NSHA18 [3]. These models excluded many events that had little-to-no instrumental data, but may have had abundant felt reports derived from surveys or newspaper reports from the time. Whilst clearly important observations, these earthquakes are associated with significant uncertainties in both their magnitude and location. Further, because these events may represent some of the largest events within the catalogue for any given region, their rates of occurrence are also poorly constrained given their rarity. The use of these data will have additional uncertainty in MFD estimation and this should be considered by formally treating uncertainty in magnitude [e.g., 46], which for any given event, will vary both in time and the method on which the preferred $M_W$ was derived.

To address ongoing challenges for catalogue improvement, Geoscience Australia is digitising printed and hand-written observations preserved on earthquake data sheets. Once complete, this information will provide a valuable resource that will allow for further interrogation of pre- and early-digital data and enable refinement of historical catalogues to improve future national-scale seismic hazard estimation. As with many aspects of seismic hazard assessment for SCRs, this is an evolving area of knowledge gain for Australia.

### 3.2 Characterising Earthquake Rates

One of the key assumptions of the NSHA18 – an outcome from the expert elicitation workshops [5] – was the adoption of a "domains-based" Gutenberg-Richer *b*-value [14] model to underpin earthquake rate calculations [1]. The rationale was such that a stable *b*-value, determined from a large geographic "domain" of relatively homogeneous continental crust [25], could be used to map a stable *b*-value to smaller zones (and smoothed seismicity) located wholly (or partially) within these domains (Fig. 2a). However, there was strong, but minority support for calculating *b*-value at the individual source-zone level [5]. Subsequent investigations revealed that the *b*-value calculations for these domains were dominated by smaller sub-regions with abundant epicentres, partially supporting this minority view. Furthermore, some sub-regions within these domains projected very different *b*-values to that of the overarching domain. Critically for earthquake risk, many of the sub-regions with potentially erroneous *b*-value assignments were in regions of high population and infrastructure density.

An alternative national-scale "smoothed" *b*-value model was developed for this study to explore the hazard sensitivity to the *b*-value assignment approach as used in the NSHA18. A series of grid points at 1, 2, 3, 4, 5, and 6-degree spacing were generated. For each grid resolution, a circular "cell" was defined with a radius roughly half of the grid spacing. Finally, for a given resolution, a second grid of cells diagonally offset by the half-grid-spacing in longitude and latitude was appended to the original grid to limit potential bias due to the regular, but indiscriminate placement of the source boundaries. For each cell within a given grid resolution, Gutenberg-Richer *b*-values were calculated using the Weichert [47] maximum likelihood method where the cell enveloped at least 50 epicentres that passed magnitude-completeness requirements within the declustered catalogue [3]. The final *b*-value grid used a hierarchical approach to assign calculated *b*-values to a finer 0.5-degree grid with the assigned value being progressively overprinted by the smallest valid cell sizes. Where multiple cells (with valid *b*-values) for a given cell resolution enveloped the final grid points, the mean *b*-value was taken. Figure 2b shows the prototype smoothed *b*-value grid. Some apparent trends in the smoothed *b*-value map can be identified with the southeastern region of the continent typically having higher *b*-values. In contrast, lower-seismicity regions on the eastern coastal margin of the continent (e.g., Sydney and Brisbane) demonstrate lower *b*-values than the domains-based model (Fig. 2a) would assign sources in the region. There is potential correspondence of the smoothed *b*-value map with the neotectonic domains. However, this correspondence requires further corroboration.

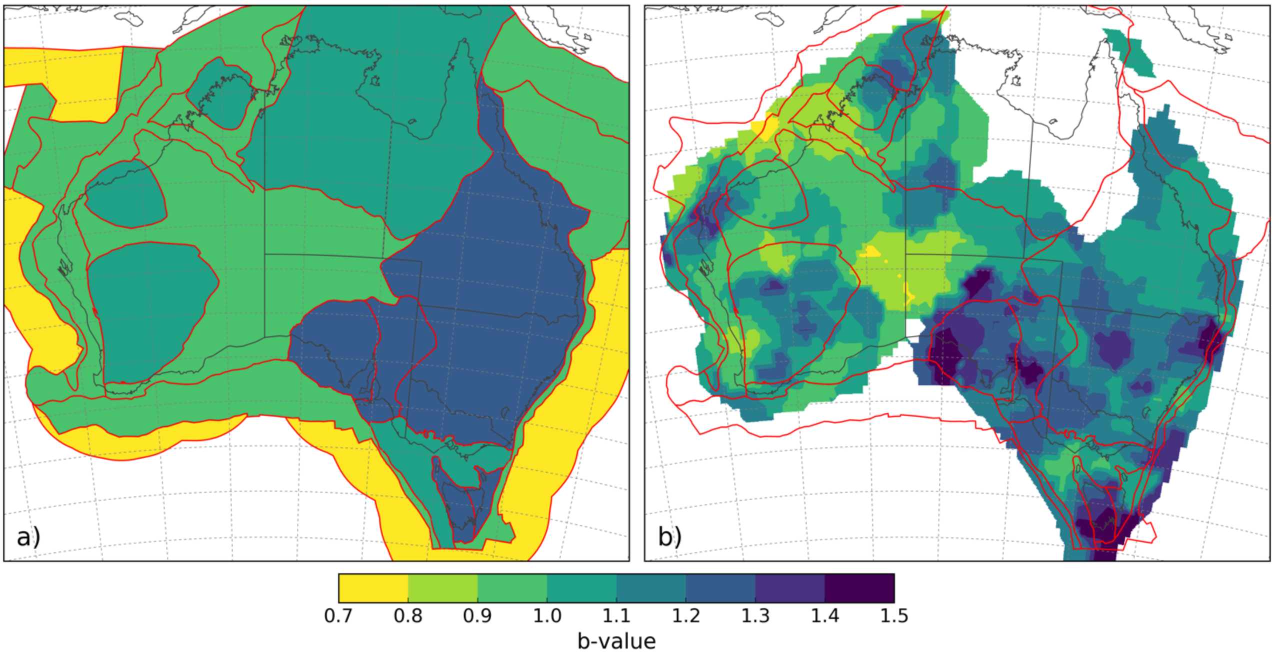

Fig. 2 – (a) The “domains-based” *b*-value model used to underpin the NSHA18, and (b) an alternative model based on a hierarchical smoothed *b*-value approach showing the variability in earthquake recurrence statistics across the country. The NSHA18 domains are superimposed on both subplots (red polygons) for reference.

The development of this alternative smoothed *b*-value map now allows for the re-characterisation of earthquake rates for the zone-based SSMs used in the NSHA18. A simplified NSHA18 SSCM using only the *background* and *regional* area sources (eight source models in total) is defined. Rather than use a “domains-based” Gutenberg-Richer *b*-value (Fig. 2a), the *regional* source models were assigned a *b*-value based on the gridded model (Fig. 2b) to calculate the zone-specific Gutenberg-Richter *a*-value using only earthquakes enveloped by the source zone. Where multiple grid points were enveloped by a zone, the average value was taken. Where no *b*-value is defined on the smoothed grid, a nearest-neighbour approach is applied. On average, use of *b*-values assigned from the gridded model fit the source-zone-specific earthquake rates better than the domains-based approach, leading to an improved estimate of earthquake activity rates. The PGA ratio of the 10% probability of exceedance in 50-year hazard map (alternative/NSHA18-based) is shown in Fig. 3a. While this map demonstrates potentially significant increases in seismic hazard up to factors of two in the state of Queensland in the country’s north-east, the hazard difference is generally less than ±0.02 g on a national scale (Fig. 3b). While only a small absolute difference, many of the regions with estimated higher hazard using the alternative source models are proximal to some of Australia’s largest population centres, making even small changes important to the overall societal risk to earthquakes.

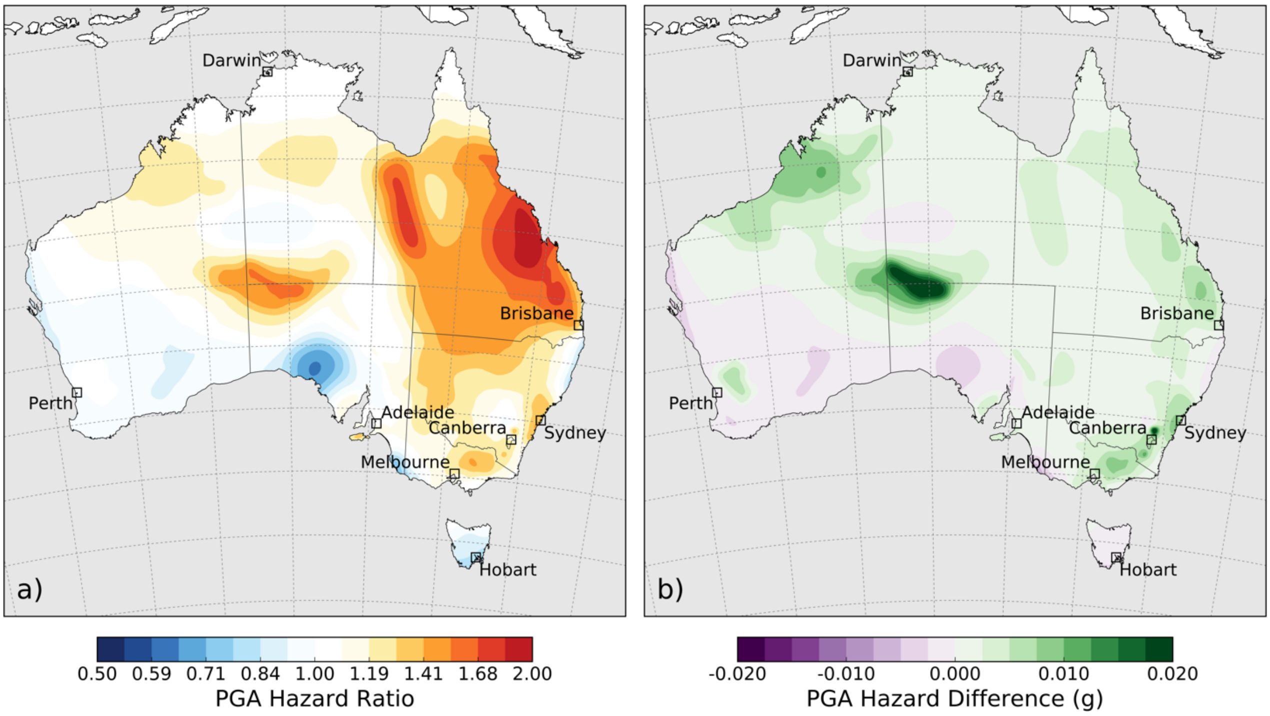

Fig. 3 – Comparison of 10% probability of exceedance in 50-year PGA hazard calculated using the simplified NSHA18 SSC and source models relative to the hazard calculated using the alternative regional source models generated using the gridded *b*-values. a) shows the ratio of the alternative hazard (the numerators) relative to the simplified NSHA18 (the devisor), while b) shows the difference between the maps (alternative – NSHA18).

### 3.3 Ground-motion models for SCRs

Australia possesses certain ground-motion characteristics that are unique to the continent, which means that it is difficult to simply use "off-the-shelf" GMMs from other SCRs [9]. The ground-motions from Australian earthquakes remain poorly characterised, particularly due to the sparse recording networks and low rates of seismicity. However, knowledge of the character of ground-motion attenuation throughout the continent is gradually evolving. Data acquired from recent Australian earthquakes [23, 48] will have significant utility to enable more informed choices for GMMs for future hazard assessments and will support future empirical and simulated ground-motion studies for the nation. Underpinning this is the need for a database of uniformly processed ground motion records from Australian earthquakes and accompanying site characterisation information similar to those developed in other regions [e.g., 49]. Ongoing enhancements to seismic monitoring networks will also provide opportunities to augment existing ground-motion datasets.

## 4. Conclusions

This manuscript presents a retrospective exploration of the successes and limitations of the NSHA18 development process. In particular, the NSHA18 succeeded in being more inclusive by accepting third-party inputs and characterising the SSCM and GMCM through a structured expert elicitation process [5]. The response from the participants of these workshops was overwhelmingly positive and the participants appreciated the opportunity to contribute towards the model's development. Whilst the expert elicitation process was highly successful in the engagement of the Australian seismological community, subsequent debate revealed that elements of the model thought to be scientifically reducible – and thus not considered epistemically uncertain – were contested by members of the community [11].

The NSHA18 resulted in significant advances in the way that seismic hazard is characterised in Australia [10]. Nevertheless, key challenges remain in our understanding of seismic hazard in slowly-deforming continental interiors. While many of these challenges will require ongoing monitoring and research, there are several opportunities to improve seismic hazard estimation by utilising existing datasets and methods that will have meaningful contributions to reducing epistemic uncertainties in future seismic hazard assessments for Australia.

## 5. Acknowledgements

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