Comparison of Australian Earthquake Models with Recorded Seismicity

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Abstract

Australian seismicity has been modelled by several authors but there has been little testing to see if the seismicity levels predicted by these models match the number of historically recorded earthquakes.

The models being studied in this paper are:

GLR	Gaull, Leiba and Rynn
AUS5	Seismology Research Centre (SRC)
RF	Risk Frontiers
GA	Geoscience Australia
RC(1-4)	Cuthbertson

The models are compared to simple recurrence relationships for the seismicity of the entire Australian continent. One such was by McCue (1993) with subsequent analysis by Sinadinovski and McCue showing a break in the linear seismicity rate at about magnitude 5.0.

An analysis using the same processing parameters as Sinadinovski and McCue but with an additional 10 years of data was conducted and no evidence of a break in seismicity rates was found. The resultant recurrence relationship (denoted OZ) was used as a benchmark against which the various seismicity models were tested.

None of the models agree and none of the models satisfactorily match the recorded seismicity rates of the new OZ relationship. This is an important conclusion for future hazard estimates.

Keywords: Australia, earthquakes, seismicity, seismicity rates.

1 - **INTRODUCTION**

Australian seismicity has been modelled by several authors in an attempt to define seismicity levels on a local level. These models are subject to large uncertainties because the detailed zonation significantly reduces the number of observations in each area.

There have been limited comparisons of the various models and even less checking if the rate of large earthquakes predicted by each model for the entire Australian region agrees with the actual number of historical recorded earthquakes.

This paper summarises the various seismicity models, compares their predicted rates of earthquakes for the Australian continent and tests these against the historical recorded seismicity.

The models being compared are:

GLR	Gaull, Leiba and Rynn (1990)
AUS5	Developed by Seismology Research Centre (SRC)
GA	Geoscience Australia - based on the work of Leonard (2008)
RF	Risk Frontiers (Hall, Dimer and Somerville, 2007)
RC(1-4)	Cuthbertson (2006, 2007)

2 – MODEL PARAMETERS

Each of the models under consideration is based on slightly different assumptions and uses slightly different methodologies.

All, apart from the GA model, are time-invariant models. However, the temporal hotspots defined in the GA model account for less than 1% of the total seismicity and so it could also be classed as time-invariant. In theory then, all models should match the recorded seismicity of the continent over the past 100 years.

2.1 – Region of interest

The Australian region in each model is defined slightly differently but it generally includes the Australian continent and continental margin, while excluding the seismicity associated with the plate boundary to the north of the continent.

In this paper there has been no normalisation to account for the slightly different areas as it is difficult with some models to define the extent of the area being studied. This may introduce some slight differences in rates but it should not have any effect on the observed b-values.

2.2 - Earthquake database

The models are based on one of two earthquake databases – either the GA national catalogue or the SRC catalogue. The SRC catalogue will be complete to a lower magnitude level in areas where SRC operates local networks – principally along the east coast of Australia. At the level of interest to this study (magnitudes above 4) it is thought that both catalogues will only have minor differences.

In all cases the models are based on a catalogue that has been either automatically or manually declustered. Again, the slight differences in declustering are thought to have only a minimal effect at the level of interest to this study (magnitudes above 4).

2.3 - Zonation

Two major methods of defining an "earthquake source zone" have been used. One is to use a simple grid; the other is to use recorded seismicity and incorporate knowledge of geologic and tectonic boundaries.

2.4 – Maximum magnitude

The Gutenberg-Richter relation has an *Mmax* value that defines the maximum earthquake magnitude that is possible in a zone. Because of the limited amount of data at the higher magnitudes this parameter is extremely difficult to determine. *Mmax* has been defined in various ways in each of the models: a simple addition to the maximum earthquake recorded; the change on slope of the magnitude-frequency curve; and by neotectonic studies.

In most cases the resultant earthquake hazard will not be significantly affected by the choice of *Mmax*.

3 - MODELS

The following is a brief summary of the salient aspects of each model under consideration.

3.1 – GLR model

Gaull, Leiba and Rynn (1990) published hazard maps for Australia for various parameters (MMI, PGA, PGV) which became the basis for the AS1170.4 Australian Earthquake Loading Code.

Their seismicity model (GLR in Figure 1) consisted of 28 zones covering Australia with an additional two zones for Indonesia and Papua New Guinea. These additional two zones have been excluded from the following analysis. They based the zones on the distribution of recorded seismicity up to the end of 1986 as well as geology and tectonic zones.

Mmax for each zone was defined as the maximum recorded earthquake in each zone plus 0.5. This approach resulted in some zones having a very low *Mmax* – as low as 4.5.

Completeness periods for each zone were determined using standard Stepp tests.

In addition to the 28 zones there were two background zones defined as simply rates per 10,000 km^2. Below magnitude 5.0 the background zones accounted for approximately 10% of the total seismicity. Above that value their influence quickly reduced to zero because of the *Mmax* used: 5.0 for western Australia and 5.5 for eastern Australia.

3.2 - AUS5 model

The AUS5 model, developed in the 1990s by the Seismology Research Centre (Brown and Gibson, 2000), has been continually updated as more earthquakes are recorded and as more sophisticated analysis techniques become available.

Approximately 118 zones are defined which are based on recorded seismicity as well as geological and tectonic features. Zones range in size from 500 km^2 to over 500,000 km^2, with more detail in areas where there is more recorded seismicity. Unlike the zonation model of GLR, the AUS5 zones cover the entire continent.

Completeness periods and b-values are determined individually for each zone, with b-values limited to be between 0.7 and 1.1. *Mmax* is set at 7.5 for all zones.

Mapped geologic faults have been gradually added to the model with various approaches used to re-evaluate the background seismicity near where a fault is located. The results in this paper (AUS5 in Figure 1) are based on an AUS5 model with no faults – ie. assuming all recorded seismicity is associated with areal zones.

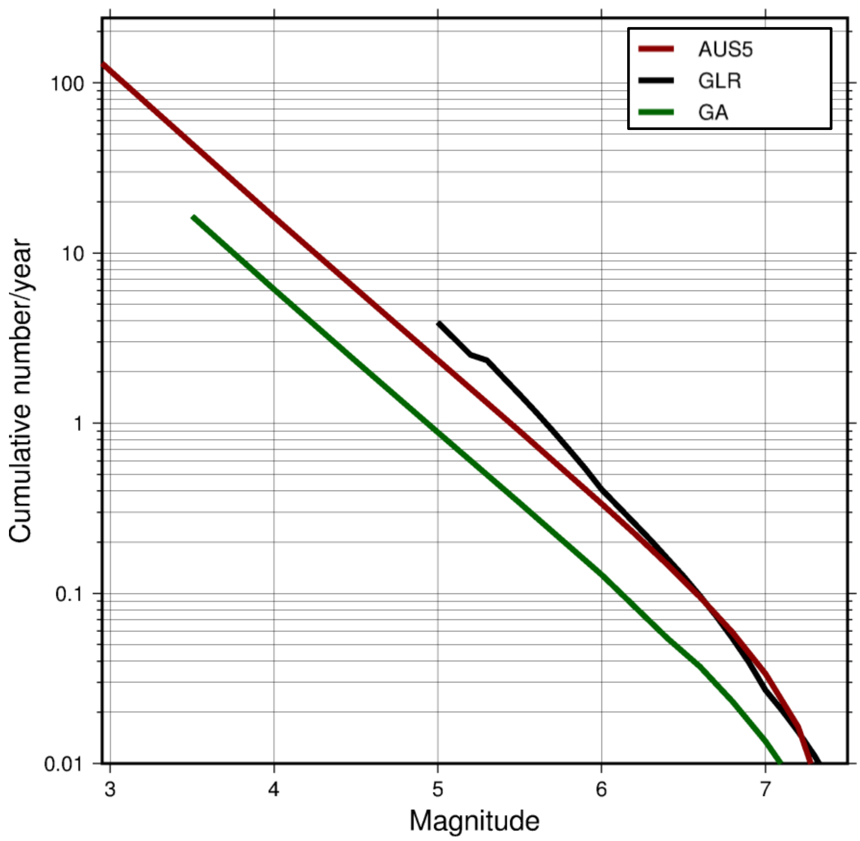

Figure 1: GLR, AUS5 and GA models.

3.3 - GA model

The Geoscience Australia hazard maps (Burbidge, 2012) are based on the seismicity model of Leonard (2008) which analysed data to the end of 2010 (Figure 1).

The analysis showed that a single Poissonian model could not account for the temporal distribution of seismicity and three layers were modelled: regional, background and hot-spots.

The 25 regional scale zones were defined using an algorithm that analysed data from a gridded analysis similar to the RF model. Grid cells of 55 km square were analysed and then the grid was moved a half a cell in each direction.

Three background areas – cratonic, non-cratonic and extended – were defined to cover the remainder of the continent.

Seismicity that appeared to be of a short term nature was modelled as 43 hot spots.

Single corner and multi-corner magnitude of completeness models were tested and showed that in a lot of cases the single corner model gave results statistically the same as a multi-corner model. Single corner models were used for 13 regional zones and a multi-corner model for 10.

The b-values were restricted to be between 0.82 and 1.15.

Background zones accounted for approximately 20% of the seismicity rates, regional zones for 80% and hotspots for less than 1%.

3.4 - RF model

The Risk Frontiers model (Figure 2), developed by Hall, Dimer and Somerville (2007), used a declustered earthquake catalogue as described in Leonard (2008). Seismicity rates determined on a grid of 10 x 10 km were smoothed with a correlation distance of 100 km in areas of higher seismicity and up to 300 km for parts with sparse seismicity.

The b-values, which ranged from 0.7 to 0.86, were calculated for four large zones and the background areas using Maximum Likelihood and Least Squares methods.

Hall et al (2007) compared the modelled and catalogue rates for M3+, 4+, 5+ and 6+ for each zone and for Australia in total. They found that 'the agreement overall is good for magnitudes up to 5, but there is a tendency for the model to over-predict the numbers of recorded earthquakes having magnitudes of 6.0 and larger.'

3.5 - RC model

The author has analysed seismicity using completeness periods that are based solely on the installed seismograph network and assumed detection functions (magnitude versus distance). This approach was used for eastern Queensland (Cuthbertson, 2006) and eastern Australia (Cuthbertson, 2007) and has since been expanded to include all of Australia.

For the Australian region a grid of 1-degree squares (~100 x 100 km) was used. Detection levels for each grid were determined from the history of seismographs installed in the area. A simple detection function (magnitude vs distance) was used to determine the magnitude of earthquakes that would be recorded in each grid square by 1, 2, 3 and 4 seismographs. This provided four different completeness curves and thus four different recurrence curves.

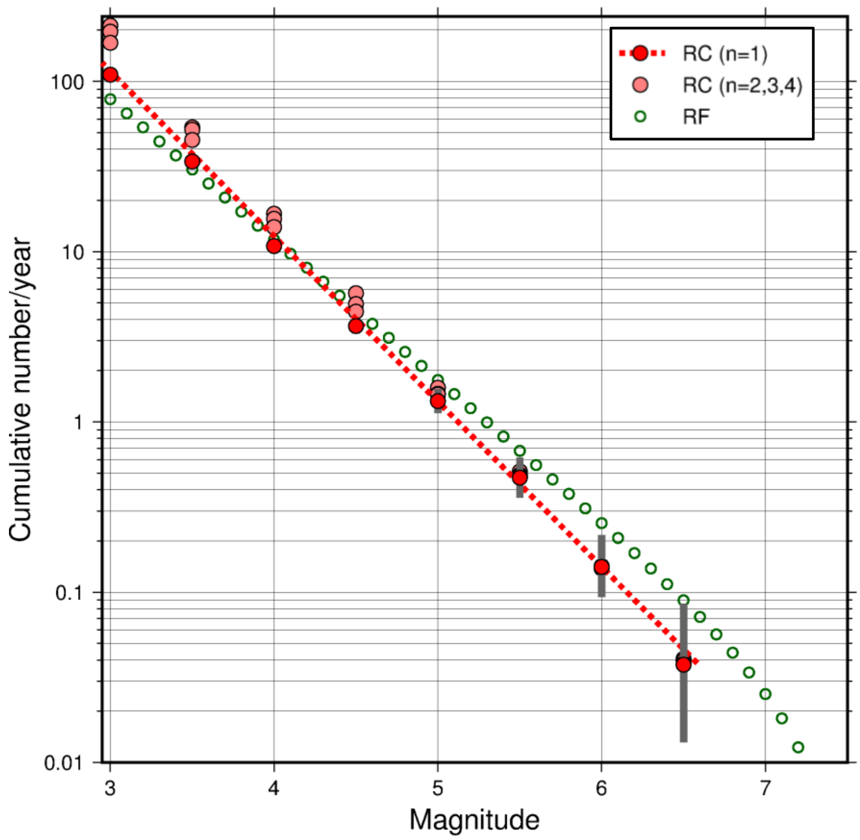

Figure 2: Risk Frontiers (RF – green) and RC (red) models. RC model for n=1 (red with fitted line and 90% error bars) and n=2, 3 and 4 (pink).

As the detection criteria is increased from one to four seismographs the b-value increases. The recurrence rates at higher magnitudes are little affected.

The choice of seismograph detection limits was based on some very rudimentary analysis of data recorded by the SRC seismograph network. Detection capabilities was based on seismograph type and operation mode (seismograph or accelerograph; continuous or triggered; analogue or digital) as well as a subjective estimate of noise levels at the site.

The methodology could be improved by performing a similar analysis of data recorded on GA and other networks. There is also a need to better estimate the detection function for sites in Western Australia.

4 – AUSTRALIAN HISTORICAL SEISMICITY

A simple recurrence relationship for the seismicity of the entire continent is required so there is something against which the above models can be compared. The relationships being considered are:

McC McCue (1993)
S&M Sinadinovski (2000) & Sinadinovski and McCue (2001)
OZ New analysis by author.
ML Leonard (2006)
AJ Johnston (1994)

4.1 - McC relationship

One of the first estimates of the rate of seismicity in Australia was by McCue (1993) who quoted the relationship:

$$\text{Log } N = 5.3 - M \qquad (\text{for } 4 \leq M \leq 7)$$

This is plotted in Figure 5. Unfortunately there is no detail as to how this relationship was obtained.

4.2 - S&M relationship

Sinadinovski (2000) used a declustered earthquake database to 2000 and a single multi-cornered completeness function (Figure 3Figure 3) to obtain a recurrence relationship for the entire continent. Sinadinovski repeated the analysis for three large zones defined from McCue et al (1998). The analysis was further discussed in Sinadinovski and McCue (2001).

In each case the authors found that a simple linear fit to the recurrence rates was not possible and two linear segments were used. The b-values for each zone varied but for the entire continent the b-value for the lower section appeared to be ~0.55, while for the upper section it was ~1.7.

Unfortunately the original Sinadinovski and McCue data are not available and the figures of Australian seismicity rates in each publication (Figure 2 in Sinadinovski, 2000 and Figure 2 in Sinadinovski and McCue, 2001), while being essentially similar, differ in several regards. In Sinadinovski (2000) the two linear segments meet between 4.9 and 5.0. In Sinadinovski and McCue (2001) the two linear segments do not meet as there is an abrupt break in rate between 4.8 and 5.0. Because the plot is of cumulative numbers this would imply an unrealistic spike in the number of earthquakes of magnitude 4.8 and 4.9. In both cases the authors quoted that there was a “significant change in slope at 5.2 ±0.1”.

The values plotted in Figure 5 have been scaled from the figure in Sinadinovski (2000).

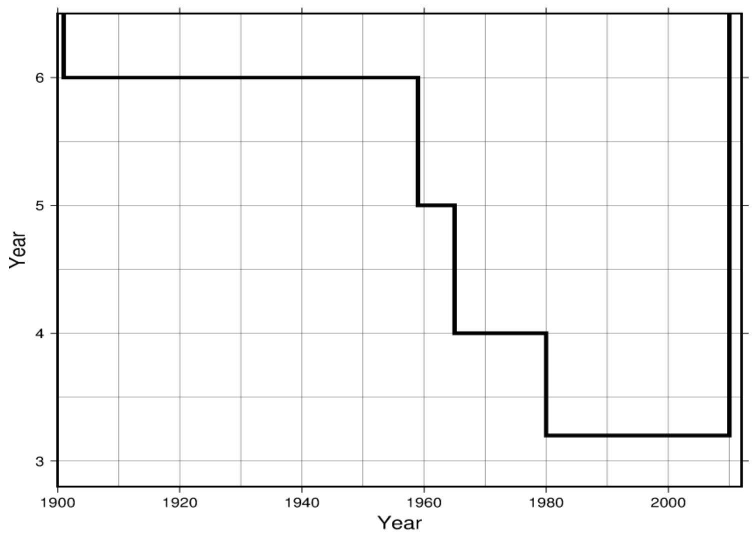

Figure 3: Magnitude completeness function of Sinadinovski and McCue (2001)

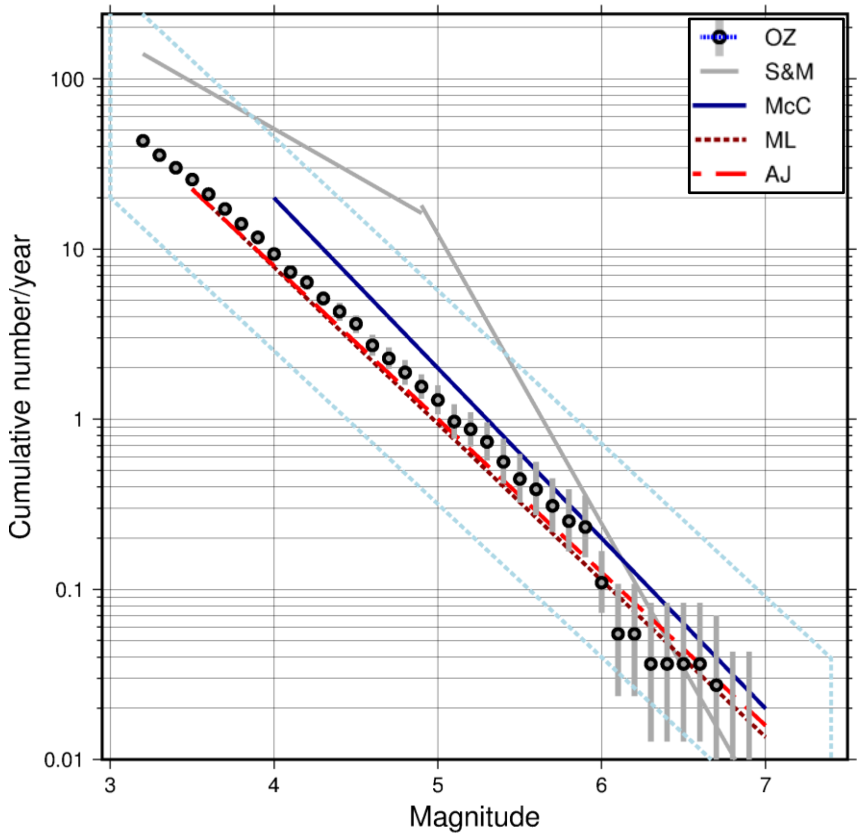

Figure 4: Australian recurrence relationships: OZ with 90% error bars, Sinadinovski and McCue (S&M), McCue 1993 (McC), Leonard 2008 (ML) and Johnstone 1994 (AJ). Light blue dotted parallelogram is area depicted in Figure 5.

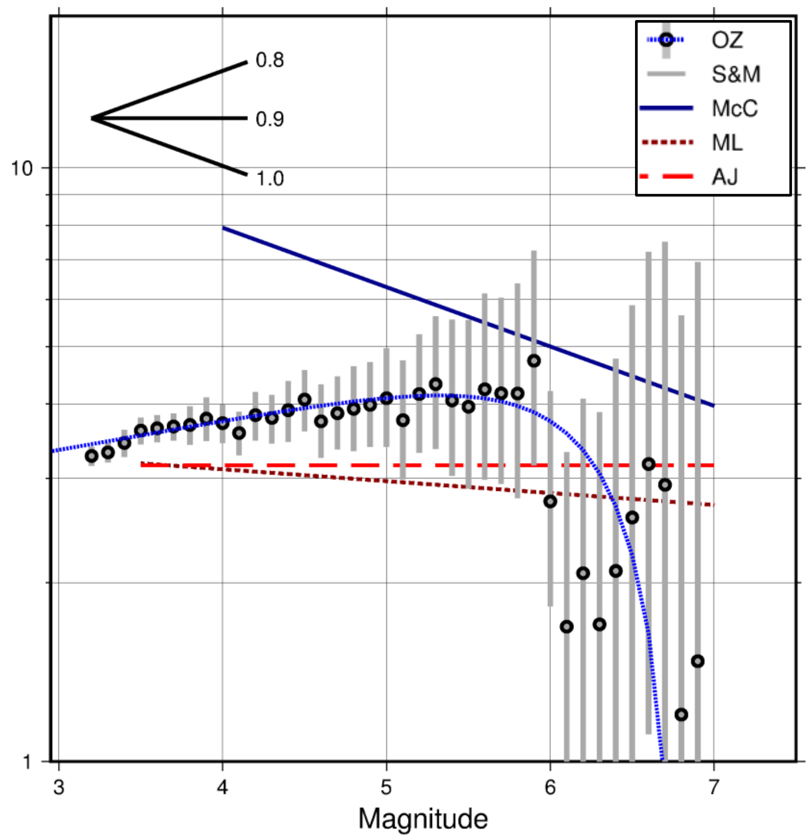

Figure 5: Australian recurrence relationships. Same as Figure 4 (without S&M) but reduced by a b-value of 0.9.

4.3 - OZ relationship

The author decided to check the results of Sinadinovski (2000) and Sinadinovski and McCue (2001) using the same magnitude completeness curve and found no evidence of a break in slope at magnitude 5 (see OZ in Figure 5). In addition, the levels of seismicity and the b-values are markedly different to those of the original publications.

This new analysis did use an additional 10 years of data (to Aug-2010) and perhaps a slightly different declustering algorithm but these could not produce the differences noted.

The analysis was repeated with a different magnitude completeness curve determined via an analysis of earthquake rates going backwards from 2010. The modified curve had only a minor effect on the results.

4.4 – ML & AJ relationships

Leonard (2008) quotes two recurrence relationships for Australian seismicity (ML and AJ in Figure 5). The first was from that paper while the second was from Johnston (1994). It is not evident how either of these relationships was determined.

4.5 – Preferred Australian recurrence relationship

In order to provide a more detailed picture the area depicted by the blue dashed line in in Figure 5 has been "reduced" by a constant b-value (b=0.9) to produce a horizontal plot which is then expanded (Figure 5). The vertical axis is now arbitrary and comparison of rates can only be made between values of the same magnitude. Lines depicting a range of b-values are plotted to help in the interpretation. The results of the S&M relationship are not depicted in this figure.

At this scale it is apparent that the rates of the OZ relationship have a consistent slope until magnitude 6. There is definitely no break in the slope as was observed in the S&M relationship. After magnitude 6 the rates appear to drop off quickly although the error bars are large.

A curve has been fitted to the OZ relationship with a b-value of 0.85 and Mmax =6.8. The b-values of the other relationships (McC = 1.0, ML = 0.92, AJ = 0.90) are all considerably higher than the OZ relationship.

Given the discrepancies between Sinadinovski (2000) and Sinadinovski and McCue (2001), the lack of detail regarding the process used to obtain the McCue (1993) relationship, and the undocumented analysis of the ML and AJ relationships, it is proposed that the OZ relationship (using the multi-cornered detection model of S&M) is a reasonable estimate of the seismicity observed in Australia over the past 100 years. As such it should be used as a benchmark against which the detailed models should be compared.

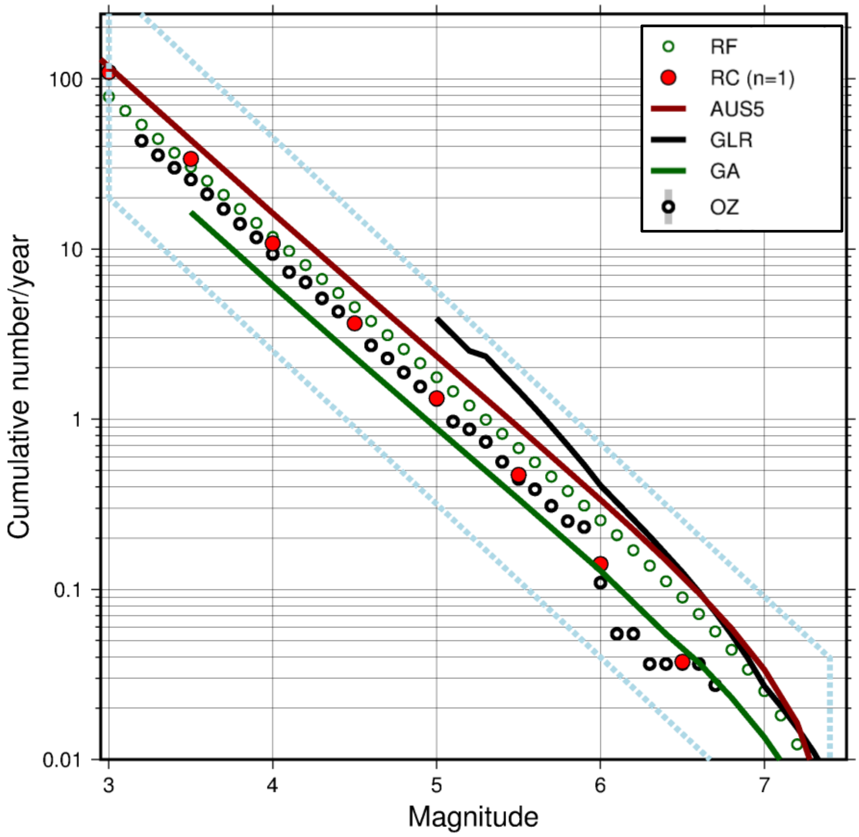

Figure 6: Combined models. Light blue parallelogram indicates area depicted in Figure 7

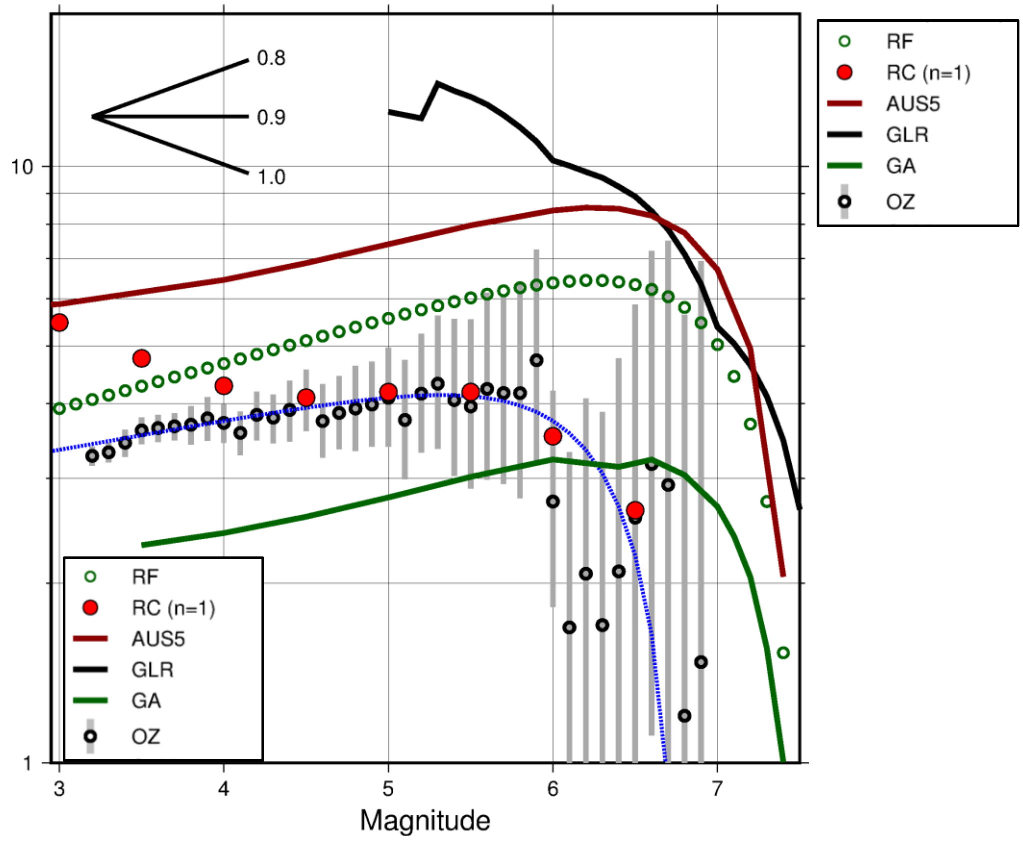

Figure 7: Combined models (as in Figure 6) reduced by a constant b-value of 0.9.

5 - COMPARISON OF MODELS

The results of all models described above are plotted in Figure 6. Only one of the RC models (for n=1) has been plotted. Figure 7 shows the same models but reduced by a b-value of 0.9 (ie. the same process as was used to convert Figure 4 into Figure 5).

Interestingly the AUS5, RF and GA models all have similar total b-values (of ~0.82-0.84) which are slightly lower than the line fitted to the OZ relationship (b=0.85). This difference is still considered significant.

This figure shows that none of the models satisfactorily matches the OZ relationship. The RC model is the only one that consistently lies within error bars of the OZ relationship between magnitudes 4 and 6. The GLR model is consistently high by a factor of ~3.5 and the AUS5 model by about 2. The RF model overestimates by about 50%. The GA model consistently under-predicts by ~30%.

None of the models appears to satisfactorily match the drop in rates above magnitude 6. One reason for this may be that the *Mmax's* being used in the models (generally 7.5) are too high and that lower *Mmax's* would better approximate the roll-off in rates above 6.

These differences in rates, especially in the magnitude range of 5 – 6 which will be where the majority of the hazard originates for routine hazard results, will have a marked effect on hazard estimates and needs to be considered in any future Australian seismicity models.

It is suggested that any future Australian seismicity model be rigorously tested to ensure it adequately matches the recorded historical seismicity. The model and the recorded seismicity should encompass a common region of interest in both cases.

6 - **REFERENCES**

Brown, A. & G. Gibson (2000) Reassessment of Earthquake Hazard in Australia. *Twelfth World Conference on Earthquake Engineering*, Auckland, New Zealand, February.

Brown, A. & G. Gibson (2004) A multi-tiered earthquake hazard model for Australia. *Tectonophysics*, 390, 25-43.

Burbidge, D. & Leonard, M. (2011) The 2012 Australian Seismic hazard map – Draft map. *AEES 2011 Barossa Valley Conference Proceedings*, Paper 8.

Gaull, B.A., Michael-Leiba, M.O. and Rynn, J.M.W. (1990) Probabilistic earthquake risk maps of Australia. Aust. Jour. Earth Sciences, Vol 37, pp169-187.

Hall, L., Dimer, F. & Somerville, P. (2007) A spatially distributed earthquake source model for Australia. *AEES 2007 Wollongong Conference Proceedings*, Paper 54.

Johnston, A. C. (1994). Seismotectonic interpretations and conclusions from the stable continental region seismicity database, in The Earthquake of Stable Continental Regions, Assessment of Large Earthquake Potential, A. C. Johnston, K. J.

Coppersmith, L. R. Kanter and C. A. Cornell (Editors), Vol. 1, *Electric Power Research Institute*, California, Chap. 4, 4-1–4-99.

Leonard, M. (2008) One hundred years of earthquake recording in Australia. *Bull. Seis. Soc. Amer.*, Vol 98, No 3, pp 1458-1470.

McCue, K. (1993) Seismicity and earthquake hazard in Australia. in Proceedings of the seminar: Earthquake Engineering and Disaster Reduction, (Eds J Wilson & C van Doorn), *Australian Earthquake Engineering Society*, Melbourne University, 25 October 1993.

McCue, K. F., Somerville, M. & Sinadinovski, C. (1998) GSHAP and the proposed Australian earthquake hazard map. *AEES 1998 Perth Conference Proceedings*, pp 18/1-5.

Sinadinovski, C. (2000) Computation of recurrence relation for Australian earthquakes. *AEES 2000 Hobart Conference Proceedings*, Paper 22.

Sinadinovski, C. & McCue, K. (2001) Recurrence relationships for Australian earthquakes. *AEES 2001 Canberra Conference Proceedings*, Paper 25.