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CONSIDERATIONS ON SEISMIC HAZARD DISAGGREGATION IN TERMS OF OCCURRENCE OR EXCEEDANCE IN NEW ZEALAND

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ABSTRACT

Probabilistic Seismic Hazard Analysis (PSHA) is widely accepted as the most robust approach for evaluating the seismic hazard at a given site and provides the basis for seismic loads in most design codes. To obtain more detailed information on the specific earthquake scenarios contributing to the hazard at a site, it is common to include seismic hazard disaggregation results within a PSHA. This is mostly done in terms of exceedance of the intensity level of interest, but for many applications a disaggregation in terms of occurrence of the intensity level of interest is more appropriate. A number of researchers have examined the theoretical differences between the exceedance and occurrence approaches; however, few have provided extensive application examples. This paper therefore compares the approaches for 24 sites across New Zealand. It is shown that the two different approaches can result in moderate differences in the mean magnitudes and site-to-source distances, as well as differences in the relative contributions from different Tectonic Region Types. Whilst some weak trends are identified, it is concluded that generally it is not possible to know *a priori* whether the difference between occurrence or exceedance approaches would have a tangible impact on disaggregation results or the results of subsequent applications. It is therefore recommended that developers of seismic hazard analysis software and providers of seismic hazard data products make both approaches readily available.

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INTRODUCTION

Seismic hazard disaggregation (or deaggregation) is an important tool in earthquake engineering and engineering seismology. It provides the analyst with an understanding of the earthquake sources that are contributing to the hazard at a site and in what proportion they contribute. Generally, disaggregation is undertaken in terms of the exceedance of a chosen ground-motion intensity; however, various researchers [1-3] have noted that for many applications a disaggregation in terms of occurrence of ground-motion intensity is more appropriate (e.g., in ground-motion selection for nonlinear time-history analyses). The theoretical background on the argument for exceedance versus occurrence was examined in some detail by Fox et al. [2], but only a single case study example was provided. This article therefore aims to provide a more in-depth, practical study on the subject by undertaking disaggregation at a number of sites across New Zealand.

Some initial background is provided on seismic hazard disaggregation and the differences between exceedance and occurrence methods are discussed. The approach adopted in the research is then outlined before examining the results in an application at 24 sites across New Zealand. Further discussion is provided for the case in which epistemic uncertainty is accounted for in the probabilistic seismic hazard analysis (PSHA) before providing conclusions and recommendations.

SEISMIC HAZARD DISAGGREGATION

Background

PSHA [4] is widely accepted as the most robust approach for evaluating the seismic hazard at a given site. The primary output from PSHA is a hazard curve, which gives the relationship between a ground-motion intensity measure, such as peak ground acceleration (*PGA*), and the rate or probability of exceedance of a given intensity. It is common to generate hazard curves in terms of spectral accelerations at a range of periods of vibration (i.e., $Sa(T)$) and then take a section through the curves at a fixed probability of exceedance (e.g., 10% in 50 years), which results in the uniform hazard spectrum (UHS) often used for design.

Whilst the UHS is suitable for many engineering applications, it does not provide the user with any information on the particular earthquake scenarios causing the hazard, which is vital information for numerous applications (see for example [3]). To better understand the earthquake scenarios contributing to the hazard at a site, seismic hazard disaggregation can be undertaken in terms of exceedance using Equation 1 (from Baker et al. [3]) below:

$$P(rup_i|IM > im) = \frac{P(IM > im|rup_i)\lambda(rup_i)}{\lambda(IM > im)} \quad (1)$$

where rup_i indicates the specific rupture scenario of interest and IM is the intensity measure being considered (e.g., spectral acceleration). The first term in the numerator of Equation 1 is the probability that a specified shaking intensity will be exceeded given the earthquake rupture scenario rup_i and the second term is the annual rate of rup_i occurring. The numerator thus gives the annual rate of exceeding im due to rup_i. The denominator is the annual rate of exceeding im regardless of the causative rupture scenario and, therefore, $P(rup_i|IM>im)$ is the probability that earthquake shaking exceeding intensity im has been caused by rup_i.

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In most practical applications, disaggregation will be undertaken in terms of magnitude (M), site-to-source distance (R) and epsilon (ε), which is the number of standard deviations a ground-motion intensity measure is above or below the mean for a given earthquake scenario. To obtain such outputs, the analyst must sum the conditional probabilities given by Equation 1 for all rup_i within the desired ranges, or “bins”, of the aforementioned parameters. Although these three variables are the most commonly considered, disaggregation can theoretically be undertaken for any of the source or path variables that affect ground-motion intensity, such as Tectonic Region Type (e.g., subduction interface, volcanic), hypocentral depth, rake angle, and many others.

Some of the applications that require knowledge of causative earthquake sources include liquefaction analysis and ground-motion selection. For liquefaction analysis, earthquake magnitude is used as proxy for ground shaking duration, which, on top of *PGA* intensity, strongly influences the extent of liquefaction. For ground-motion selection, modern, sophisticated approaches, such as the Conditional Mean Spectrum [5] or Generalised Conditional Intensity Measure approach [6] are entirely dependent on knowing the dominant earthquake sources contributing at the intensity of interest. However, it is worth noting that disaggregation is also generally required for more conventional ground-motion selection in accordance with the New Zealand seismic loading standard, NZS1170.5 [7]. NZS1170.5 states that selected ground motions must “have a seismological signature (i.e., magnitude, source characteristics (including fault mechanism) and source-to-site distance) the same as (or reasonably consistent with) the signature of the site”. For most sites in New Zealand, it will be necessary to undertake disaggregation to obtain this “seismological signature”.

Exceedance vs. Occurrence

Most commonly, disaggregation is carried out in terms of exceedance, as per Equation 1, and generally the providers of seismic hazard data products, such as the United States Geological Survey (USGS), will provide disaggregation data in this form. As the name implies, disaggregation in terms of exceedance will give the distribution of M, R, E (or other desired variables) for all earthquake scenarios that cause the exceedance of a specific ground-motion intensity, such as the spectral acceleration corresponding to the first mode period of vibration of a structure and a 475-year return period ($Sa(T_1)_{\mathrm{RP}=475}$). However, for most seismic analyses (e.g., the nonlinear time-history analysis of a structure) the analyst is instead interested in understanding the response of a structure or system when subjected to ground motions exactly at a specific intensity (rather than above said intensity). In these cases, it is in principle more appropriate to use disaggregation in terms of occurrence, i.e., the analyst is interested in knowing which earthquake scenarios cause the shaking at the intensity being considered rather than which ones exceed it.

To disaggregate in terms of occurrence, the $IM > im$ terms in Equation 1 are replaced by $IM = im$. However, because PSHA is undertaken using a discrete summation, rather than a continuous integral, it is not possible to obtain an exact disaggregation in terms of occurrence of a given intensity. Instead, one must consider a narrow “band” of hazard about the intensity of interest as per Equation 2:

$$P(rup_i|IM = im) \cong P(rup_i|im < IM < im + \delta) = \frac{P(IM > im|rup_i)\lambda(rup_i) - P(IM > im + \delta|rup_i)\lambda(rup_i)}{\lambda(IM > im) - \lambda(IM > im + \delta)} \qquad (2)$$

where δ is a small increment in im. This could be considered to make disaggregation in terms of occurrence more challenging because the analyst must apply some judgement to determine appropriate values for im and δ. However, Fox et al. [2] showed that occurrence disaggregation output is relatively insensitive to the size of the “band”, so long as it is in a sensible range. Furthermore, if banded disaggregation were implemented in PSHA software, this could remove the need for subjectivity on the part of the analyst.

APPROACH

To examine the differences between exceedance and occurrence disaggregation in New Zealand, 24 sites across the country were studied (see Table A1). These sites correspond to the same 24 geographic locations used in a recent study by Bradley et al. [8], which allows for a convenient benchmarking of results.

PSHA

For each site, a PSHA was carried out to obtain hazard curves that cover the range of return periods from 25 to 2500 years. Again, to allow for benchmarking of results, the general PSHA approach used in [8] was adopted. That is, the Seismic Source Model of Stirling et al. [9] (available at www.gns.cri.nz) was used and all sites were assumed to have an average shear-wave velocity in the top 30 m of soil of $V_{S,30}$ = 300 m/s.

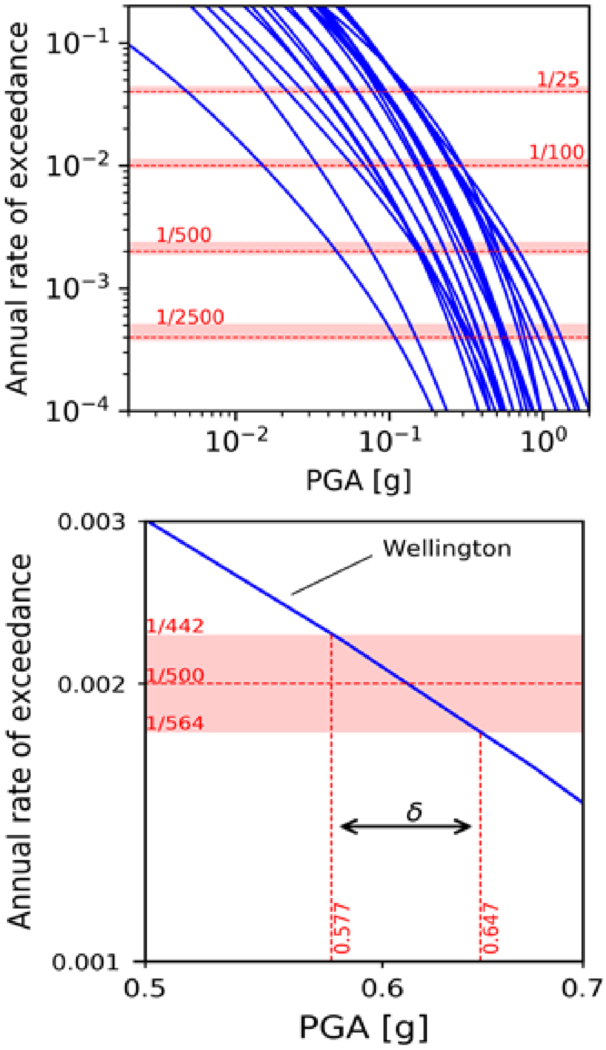


Figure 1: Top: PGA seismic hazard curves for all 24 sites and the corresponding bands of hazard (red shaded) used for disaggregation in terms of occurrence. Bottom: Band corresponding to the 500 year return period for Wellington.

Four Ground-Motion Models (GMMs) were used, one for each Tectonic Region Type (TRT) in the Source Model. Although the use of one GMM per TRT means that epistemic uncertainty cannot be estimated, it was decided that this drawback was outweighed by the benefits of keeping the PSHA simple. For Active Shallow Crustal and Volcanic regions, the Bradley [10] model was adopted on the basis that it is the only recent GMM that has been developed specifically for New Zealand. For Subduction Interface and Subduction Slab sources, the model of Abrahamson et al. [11] was adopted. This was chosen over the Zhao et al. [12] GMM, which, for very large magnitude events, has been observed to diverge from other globally applicable subduction GMMs, predicting exceedingly high values [13]. It is noted that the Bradley [10] model uses the $Z_{1.0}$ depth parameter as one of its inputs. To obtain a generic estimate of $Z_{1.0}$, the recommended equations of Abrahamson and Silva [14] were used, which yielded a depth of $Z_{1.0} = 459$ m.

Three different intensity measures were considered for the PSHA, *PGA*, *Sa*(0.5) and *Sa*(2.0), and the calculations were performed using the OpenQuake Engine v3.11 [15].

Disaggregation

The OpenQuake Engine was then used to undertake seismic hazard disaggregation for the 24 sites. Return periods of 25, 100, 500 and 2500 years were considered, so the impacts of exceedance versus occurrence could be investigated for both frequent and rare events. Bin widths for magnitude, distance and epsilon of 0.5, 10 km, and 1.0 were used, respectively.

Before carrying out the disaggregation in terms of occurrence, a decision had to be made on an appropriate band of intensity to consider. As a pragmatic option, it was decided to consider a band of ± 5 % about the intensity of interest (i.e., $im = 0.95x$ and $im+\delta = 1.05x$). For practical implementation using the OpenQuake Engine, the corresponding return periods for these upper and lower intensities were determined for each site. It was found that the return periods varied very little from site to site and therefore the average values were adopted for all cases (Table 1). The concept of the bands used for disaggregation in terms of occurrence is illustrated in Figure 1.

Table 1: Return periods for seismic hazard disaggregation.

Exceedance [yrs]	**Occurrence [yrs]**
25	23.1 – 27.0
100	90.6 – 110
500	442 – 564
2500	2139 - 2899

RESULTS

Mean Magnitude and Distance

For each site, intensity and return period, the mean magnitude and site-to-source distances were calculated using equations 3 and 4:

$$\bar{M} = \sum M_i \times P(M_i | IM > im) \tag{3}$$

$$\bar{R} = \sum R_i \times P(R_i | IM > im) \tag{4}$$

where M_i and R_i are i^{th} magnitude and distance bins, respectively (in the occurrence case the $IM > im$ term is replaced by $IM = im$).

The results are shown graphically in Figure 2 and all data are reported in Table A1. It can be observed that, generally, there is a trend for the disaggregation in terms of occurrence to return smaller mean magnitudes and larger mean site-to-source distances. This is expected given that larger magnitudes and shorter distances lead to higher ground-motion intensities. It can also be observed that the extent to which the mean $\bar{M}$, $\bar{R}$ pair changes, depending on whether occurrence of exceedance is considered, varies substantially between the different sites, return periods and intensity measures.

To examine these results in more detail and identify any relevant trends, the difference in mean magnitude and distance for the exceedance and occurrence cases, referred to as $\Delta\bar{M}$ ($=\bar{M}_{oc.} - \bar{M}_{ex.}$) and $\Delta\bar{R}$ ($=\bar{R}_{oc.} - \bar{R}_{ex.}$), are plotted in Figure 3. It can be observed that there is a significant variation in $\Delta\bar{M}$ and $\Delta\bar{R}$ for individual cases. $\Delta\bar{M}$ ranges between -0.46 and 0.17 while $\Delta\bar{R}$ ranges between -4.9 and 55.6 km. Considering the average $\Delta\bar{M}$ and $\Delta\bar{R}$ across all sites, there is a weak trend of $\Delta\bar{M}$ and $\Delta\bar{R}$ both increasing (in an absolute sense) as the return period decreases. There is a similar weak trend for $\Delta\bar{R}$ to increase as the period of vibration of the spectral acceleration increases; however, the same observation is not made for $\Delta\bar{M}$. Further investigations were undertaken to identify whether there were any trends in terms of the seismicity at each of the 24 sites (i.e. low, medium or high seismicity) and it was found that typically $\Delta\bar{M}$ and $\Delta\bar{R}$ both decrease with increasing site intensity. However, this is dependent on the intensity measure type (i.e., *PGA*, *Sa*(0.5), *Sa*(2.0)) and return period, as illustrated previously.

Mean magnitude and distance are useful statistics for gaining an understanding of the difference between exceedance and occurrence disaggregation; however, for some applications it is not sufficient to know just the mean *M*, *R* pair, and the full distribution of magnitude and distance may be required. Figure 4 shows the full distribution of magnitude and distance for $Sa(0.5)_{RP=25}$ at the Wellington site. Here it can be seen that the distribution of contributing magnitudes and distances changes substantially. In the exceedance case there is a substantial contribution from large nearby earthquakes from sources including the Wellington-Hutt Valley segment of the Wellington fault and the Hikurangi subduction zone (interface). On the other hand, in the occurrence case these large nearby events do not contribute at all, and instead the hazard is dominated by smaller magnitude contributions from the background seismicity. This difference is most pronounced for short return periods and reduces significantly with increasing return period.

One will also note in Figure 4 that for the occurrence case the range of epsilon for each bin is significantly reduced. This is an obvious result of each *M*, *R* pair having to produce a ground-motion intensity that exactly equals the intensity of interest rather than exceed it.

Tectonic Region Type

The same exercise was repeated considering disaggregation for Tectonic Region Type instead of magnitude and distance. The results are shown in Figure 5 for *Sa*(0.5) hazard at the 500-year return period. For sites with contributions from multiple TRTs, there can be a substantial difference in their relative contributions when considering the exceedance or occurrence approaches. The most extreme change is in the case of Palmerston North, where it can be seen that going from the exceedance case to the occurrence case the percentage contribution from subduction interface sources (in this case the Hikurangi subduction zone) reduces by over 20%. As the total percentage contribution must sum to 100%, this is compensated

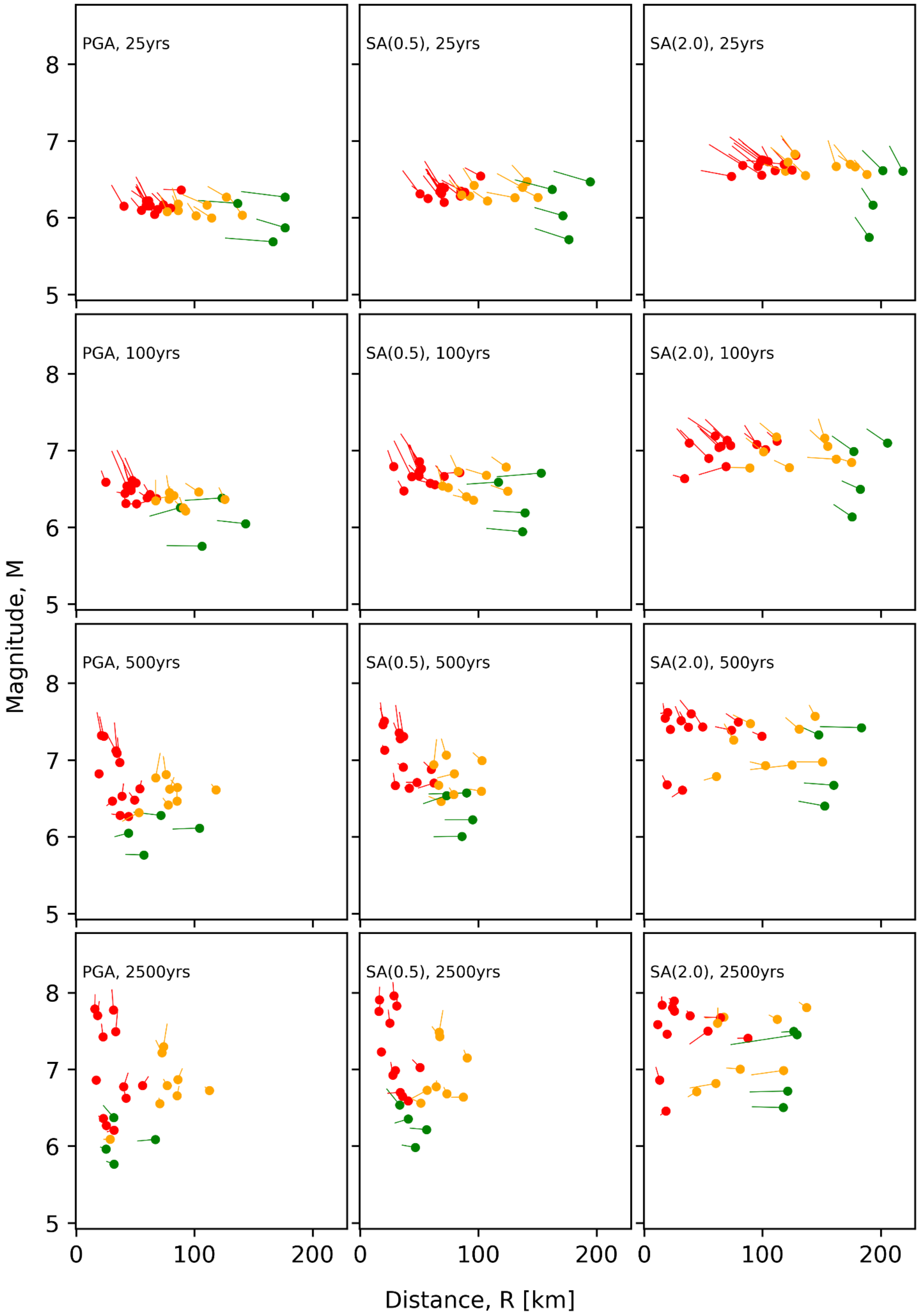


Figure 2: Mean magnitude and distance pairs for all sites, intensity measures and return periods. The circular marker indicates the disaggregation in terms of occurrence, whereas the opposite end of the line indicates the value for disaggregation in terms of exceedance (therefore the longer the line the larger the difference). The green, orange and red colours correspond to sites of low, medium and high hazard, respectively, based on NZS1170.5 hazard factor, Z (Low: $Z \leq 0.15$, Medium: $0.15 \leq Z < 0.3$, High: $0.3 < Z$).

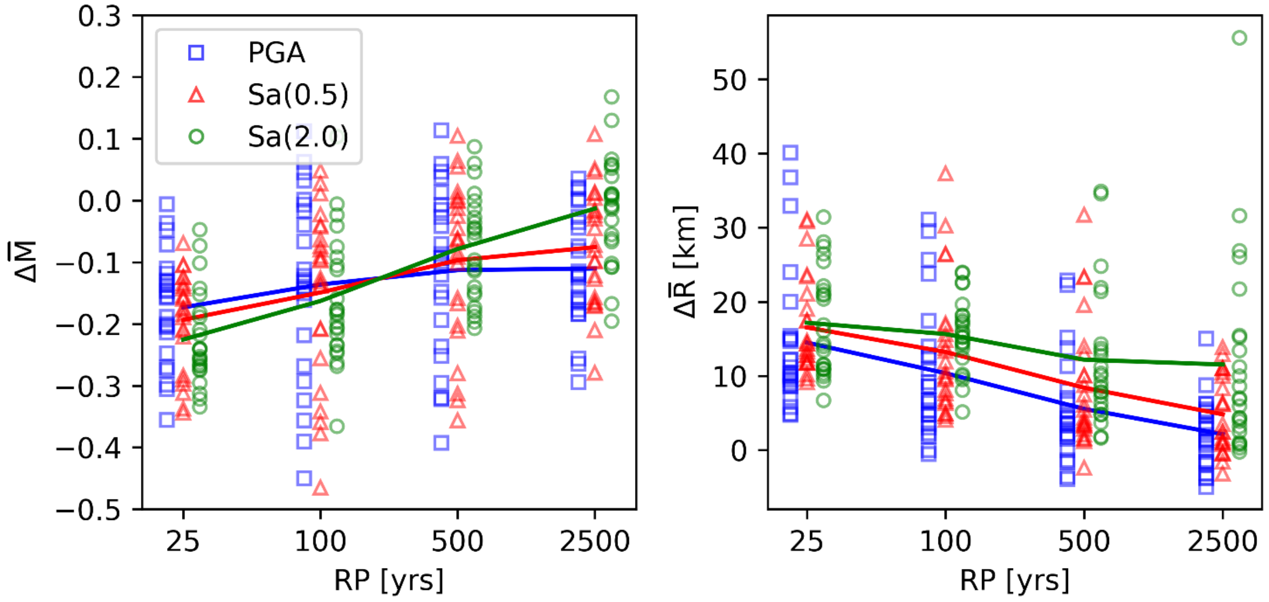


Figure 3: Difference in mean magnitude ($\Delta\bar{M}$) and difference in mean distance ($\Delta\bar{R}$) between exceedance and occurrence cases. Markers indicate individual sites and lines indicate the average across all sites. Markers have been horizontally offset for different intensity measures to assist in the clarity of the figure.

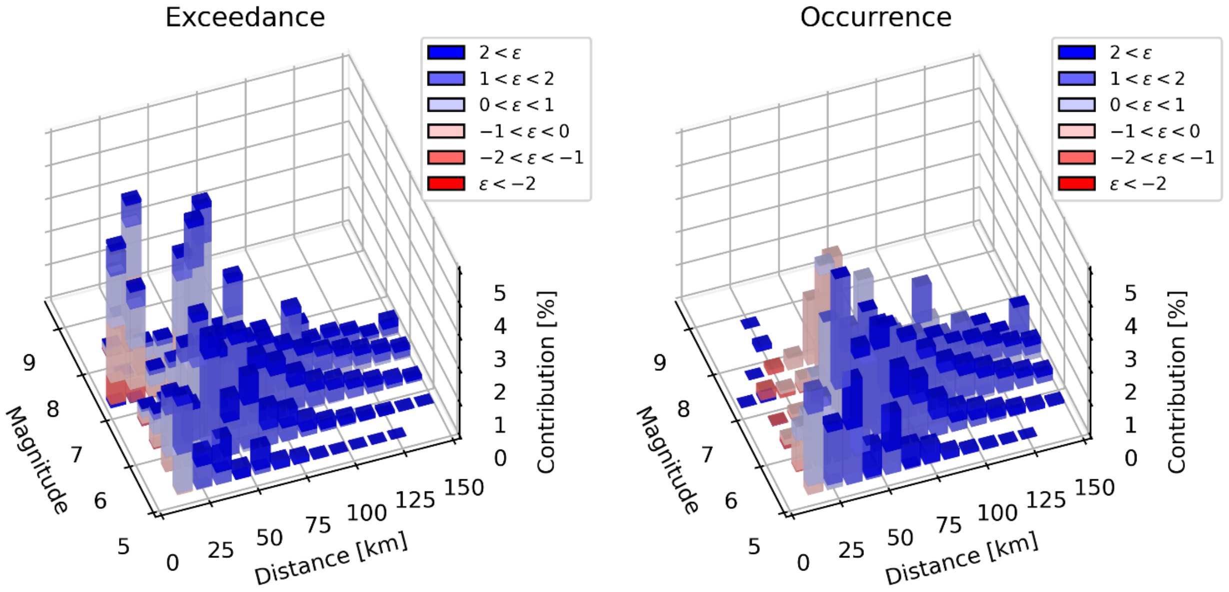


Figure 4: Disaggregation of Sa(0.5) hazard for Wellington at a return period of 25 years. Exceedance on the left and occurrence on the right.

for by a relative increase in the contributions from active shallow crustal and subduction slab sources.

The importance of the Tectonic Region Type becomes apparent when considering applications such as ground-motion selection using the conditional mean spectrum [6]. In the conditional mean spectrum approach, ground motions are selected to match the spectral shape corresponding to a specific GMM. The choice of GMM would clearly change depending on whether the hazard at a site is dominated by, say, active shallow crustal or subduction interface events.

CONSIDERATION OF MULTIPLE SOURCE AND GROUND-MOTION MODELS

The New Zealand National Seismic Hazard Model is currently in the process of being revised [16], and one of the likely revisions is the inclusion of multiple source models and ground-motion models. This offers the substantial benefit of providing users of seismic hazard data products with a measure of the epistemic uncertainty in the hazard estimates; however, it comes with the cost of more complexity in calculations and in the interpretation of outputs.

One relevant question is that of whether to use the mean, median, or some other statistic when reporting seismic hazard results. Abrahamson and Bommer [17] provide an argument for the use of fractile hazard curves instead of the mean hazard; however, the argument does not extend to disaggregation. One possible approach, if using, say, the median hazard curve as an example of a fractile, would be to disaggregate for the particular logic-tree realization that produces the hazard closest to the median. However, there is no guarantee that the disaggregation of this particular realization would yield any sort of central tendency. For example, it could be the case that a particular combination of GMMs gives unusually high intensities for subduction interface events and unusually low intensities for active shallow crustal earthquakes. This would result in a disaggregation that shows a much larger contribution for subduction interface events when compared to other realizations but could still potentially result in a hazard curve that is close to the median. Furthermore, a single realization may represent only a very small weight amongst all paths of the logic tree.

To illustrate this point, Figure 6 shows the disaggregation for PGA hazard in Wellington for a return period of 500 years using the ground-motion logic tree of [8] (which results in a total of 16 realizations). The disaggregation for the single realization closest to the median (realization 2) shows a contribution from earthquakes having a magnitude and distance of approximately 7.0 and 50 km, respectively, which are not as prominent in the mean disaggregation. Instead, the mean disaggregation shows a larger contribution from large magnitude (M > 7.5) and short distance events (mainly the Wellington-Hutt Valley segment of the Wellington fault).

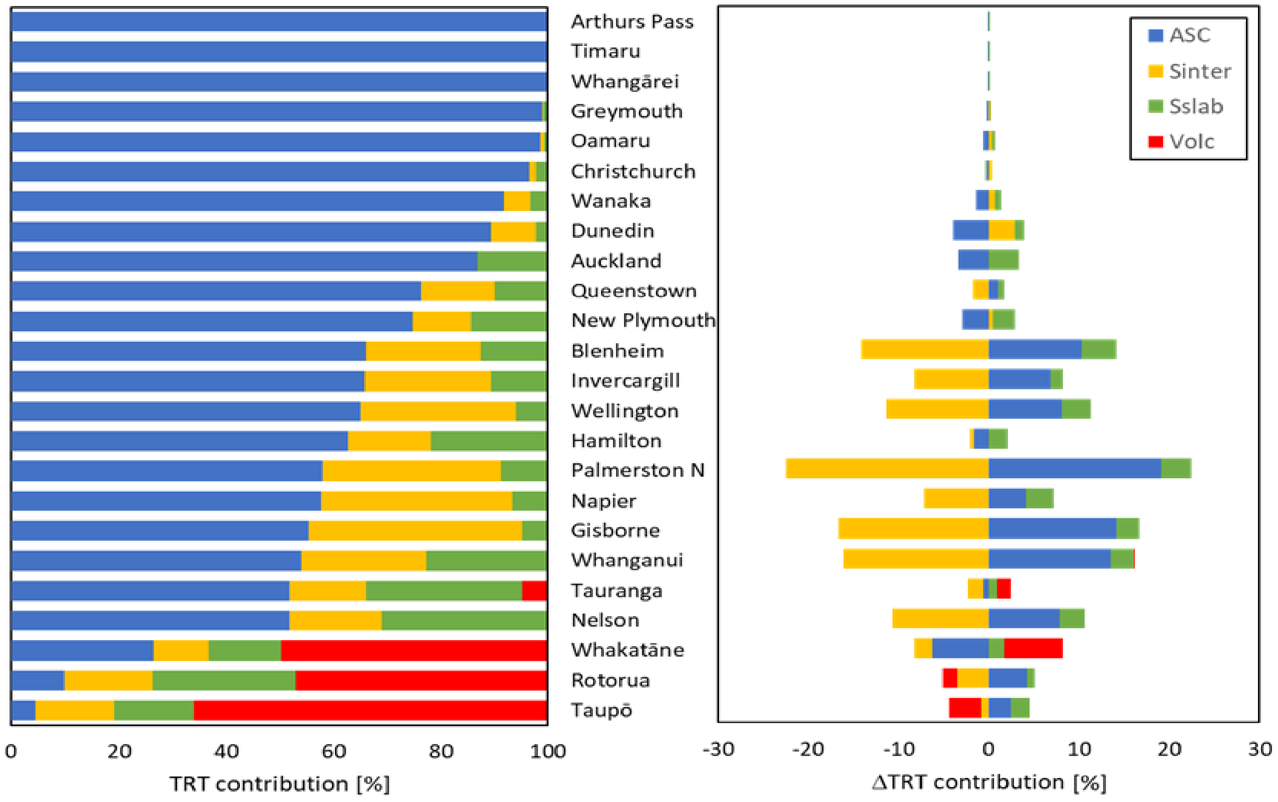
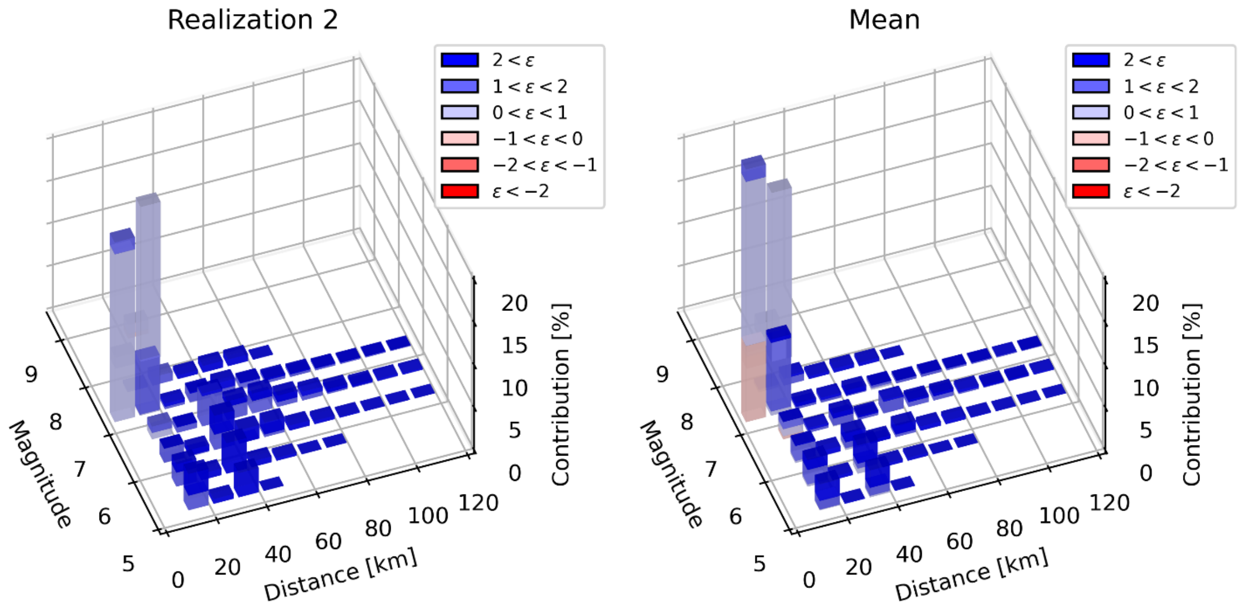


Figure 5: Disaggregation of Sa(0.5) hazard at a return period of 500 years.
On the left hand side is the percentage contribution of each TRT using the occurrence approach. On the right hand side is the difference between the exceedance and occurrence approaches in terms of percentage contribution from each TRT.


Realization 2

Mean

Figure 6: Occurrence disaggregation of PGA hazard for Wellington at a return period of 500 years.
On the left disaggregation for the single realization closest to the median and on the right the mean disaggregation.

CONCLUSIONS AND RECOMMENDATIONS

This research has generated seismic hazard disaggregation data for 24 sites distributed across New Zealand, using both the exceedance and occurrence approaches. From these data the following conclusions can be drawn:

- Disaggregation in terms of occurrence will tend to result, on average, in mean magnitudes that are smaller and mean distances that are larger than those obtained from disaggregation in terms of exceedance. The size of the difference, for both magnitude and distance, varies significantly between sites and depends on the intensity measure and return period considered.
- By aggregating the data across all sites, some weak trends could be identified. The difference between the two disaggregation approaches, measured in terms of $\Delta\bar{M}$ and $\Delta\bar{R}$, tends to increase as return period decreases. A similarly weak trend shows $\Delta\bar{R}$ increasing as the period of vibration of the spectral acceleration increases
- Whilst mean magnitude and distance provide an effective metric for comparison across many sites, they provide no information on the shape of the M, R distribution. It was shown that this can change significantly when considering exceedance or occurrence, with some events that contribute significantly in the exceedance case all but disappearing in the occurrence case.
- Related to the previous point, it was shown that the two different approaches can lead to significant differences in the relative contribution of different Tectonic Region Types.
- Caution should be exercised when considering how to disaggregate in the case of PSHA that uses multiple source models or ground-motion models. Adopting the disaggregation of the single realization closest to the mean or median is not recommended; instead, the disaggregation for the full mean hazard should be used.

With the above in mind, it can be concluded generally that considering occurrence disaggregation instead of exceedance disaggregation has a moderate impact on the disaggregation outputs. Although some weak trends were identified, it is not possible to determine *a priori* whether there would be a significant difference in either the disaggregation output or the results of the application to which they are applied.

Common PSHA software and the providers of seismic hazard data often give disaggregation in terms of exceedance only, and it can be cumbersome to obtain disaggregation in terms of occurrence. The analyst is therefore left, in such instances, with a decision of whether to spend time on obtaining disaggregation in terms of occurrence or accept that there is a risk of some bias being introduced into their analysis. To alleviate this problem, it is recommended that providers of PSHA software include disaggregation in terms of occurrence as an analysis option. Similarly, where disaggregation data is made available by seismic hazard data providers, this should be provided in terms of both exceedance and occurrence or, at a minimum, the underlying models should be made openly accessible for use by others in practical applications and research (as is currently the case in New Zealand).

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APPENDIX

Table A1: Mean magnitudes and site-to-source distances from disaggregation.

Site	RP [yrs]	*PGA*				*Sa*(0.5)				*Sa*(2.0)			
		M		*R* [km]		*M*		*R* [km]		*M*		*R* [km]	
		Ex.	Occ.	Ex.	Occ.	Ex.	Occ.	Ex.	Occ.	Ex.	Occ.	Ex.	Occ.
Arthurs Pass	25	6.4	6.2	30	40	6.6	6.3	36	51	7.0	6.7	55	83
	100	6.7	6.6	21	25	7.0	6.8	23	28	7.3	7.1	28	38
	500	6.8	6.8	18	19	7.2	7.1	19	21	7.4	7.4	20	22
	2500	6.9	6.9	16	17	7.2	7.2	17	18	7.5	7.5	18	19
Auckland	25	6.0	5.9	153	177	6.1	6.0	148	171	6.4	6.2	184	193
	100	6.1	6.0	120	143	6.2	6.2	113	139	6.6	6.5	167	183
	500	6.1	6.1	82	104	6.2	6.2	72	95	6.7	6.7	135	160
	2500	6.1	6.1	52	67	6.2	6.2	42	56	6.7	6.7	90	121
Blenheim	25	6.4	6.2	51	59	6.6	6.3	56	67	7.0	6.8	80	101
	100	6.8	6.5	41	46	7.1	6.7	42	50	7.4	7.1	52	70
	500	7.3	7.0	35	37	7.6	7.3	33	37	7.8	7.6	30	40
	2500	7.7	7.5	35	33	8.0	7.8	31	31	7.9	7.9	21	25
Christchurch	25	6.4	6.4	74	89	6.6	6.5	89	102	7.0	6.8	117	128
	100	6.3	6.4	54	68	6.7	6.7	71	84	7.2	7.1	104	112
	500	6.2	6.3	36	44	6.6	6.7	49	62	7.4	7.3	92	100
	2500	6.2	6.2	26	32	6.5	6.6	32	41	7.4	7.4	79	88
Dunedin	25	6.3	6.3	140	177	6.6	6.5	164	195	6.9	6.6	208	219
	100	6.3	6.4	92	123	6.7	6.7	116	153	7.3	7.1	188	206
	500	6.3	6.3	49	72	6.6	6.6	58	90	7.4	7.4	149	184
	2500	6.5	6.4	23	32	6.7	6.5	22	33	7.3	7.5	73	129
Gisborne	25	6.4	6.0	51	66	6.5	6.2	54	71	6.8	6.6	72	99
	100	7.0	6.5	30	43	7.1	6.7	29	44	7.3	6.9	31	55
	500	7.6	7.3	18	21	7.7	7.5	17	19	7.7	7.5	16	18
	2500	8.0	7.8	16	16	8.1	7.9	16	16	7.9	7.8	15	15
Greymouth	25	6.3	6.2	47	59	6.6	6.4	57	71	7.0	6.7	84	105
	100	6.5	6.4	35	41	6.8	6.7	41	50	7.3	7.1	59	73
	500	6.4	6.5	26	31	7.0	6.9	32	36	7.6	7.4	43	49
	2500	6.3	6.4	20	23	7.0	7.0	26	30	7.8	7.7	36	39
Hamilton	25	6.2	6.0	130	140	6.4	6.3	133	150	6.7	6.6	178	188
	100	6.5	6.4	121	126	6.5	6.5	111	125	6.9	6.8	159	175
	500	6.7	6.6	115	118	6.6	6.6	93	103	7.0	7.0	129	151
	2500	6.8	6.7	109	113	6.6	6.6	77	87	6.9	7.0	91	118
Invercargill	25	6.4	6.3	112	127	6.7	6.5	129	141	7.0	6.7	156	162
	100	6.6	6.5	93	104	6.9	6.8	111	123	7.4	7.2	147	153
	500	6.7	6.6	80	86	7.1	7.0	96	103	7.7	7.6	140	144
	2500	6.9	6.8	74	77	7.2	7.1	88	90	7.9	7.8	131	137
Napier	25	6.5	6.2	54	63	6.6	6.3	57	69	6.9	6.7	75	96
	100	6.9	6.6	41	51	7.1	6.8	42	52	7.3	7.0	47	63
	500	7.3	7.1	27	34	7.5	7.3	28	34	7.6	7.4	30	37
	2500	7.6	7.4	21	23	7.8	7.6	24	25	7.9	7.8	21	26
Nelson	25	6.4	6.2	81	86	6.6	6.4	87	96	7.1	6.8	116	127
	100	6.7	6.5	76	79	6.9	6.7	76	83	7.4	7.2	98	112
	500	7.0	6.8	74	76	7.3	7.1	69	73	7.6	7.5	75	90
	2500	7.4	7.2	67	73	7.6	7.4	61	67	7.7	7.7	52	67
New Plymouth	25	6.1	6.0	100	115	6.3	6.3	107	131	6.8	6.7	164	178
	100	6.3	6.2	84	92	6.4	6.4	79	96	6.9	6.9	138	162
	500	6.5	6.4	74	78	6.5	6.5	58	68	6.9	6.9	90	125
	2500	6.6	6.6	70	71	6.6	6.6	45	51	6.8	6.8	39	61
Oamaru	25	6.2	6.2	104	136	6.5	6.4	131	162	6.9	6.6	185	202
	100	6.1	6.3	62	88	6.6	6.6	90	117	7.2	7.0	159	177
	500	6.0	6.0	33	44	6.4	6.5	54	73	7.4	7.3	134	147
	2500	6.0	6.0	21	25	6.3	6.4	29	41	7.5	7.5	116	126
Palmerston North	25	6.4	6.2	51	61	6.6	6.3	56	69	7.0	6.7	76	98
	100	6.9	6.5	39	46	7.1	6.7	40	50	7.3	7.1	45	65
	500	7.5	7.1	32	35	7.7	7.4	30	33	7.7	7.5	26	31
	2500	8.0	7.8	30	32	8.1	8.0	28	29	7.9	7.8	23	24
Queenstown	25	6.3	6.2	64	74	6.6	6.3	75	85	6.9	6.6	100	111
	100	6.5	6.4	54	60	6.8	6.7	64	71	7.3	7.1	85	95
	500	6.6	6.5	45	49	7.0	6.9	54	60	7.6	7.5	69	79
	2500	6.8	6.6	40	42	7.1	7.0	44	51	7.7	7.7	51	65
Rotorua	25	6.3	6.1	82	86	6.4	6.3	81	92	6.7	6.6	99	119
	100	6.5	6.4	79	79	6.6	6.5	70	74	6.8	6.8	72	89
	500	6.8	6.6	83	79	6.7	6.7	65	66	6.7	6.8	51	61
	2500	7.0	6.9	90	86	6.8	6.8	65	64	6.6	6.7	37	44
Taupō	25	6.3	6.1	69	80	6.5	6.3	69	88	6.7	6.7	87	118
	100	6.6	6.4	57	62	6.6	6.6	48	59	6.7	6.8	47	69
	500	6.7	6.6	55	54	6.6	6.6	38	42	6.5	6.6	24	32
	2500	6.9	6.8	61	56	6.7	6.7	35	36	6.4	6.5	14	18

Table A1: Mean magnitudes and site-to-source distances from disaggregation (continued).

Site	RP [yrs]	*PGA*				*Sa*(0.5)				*Sa*(2.0)			
		M		*R* [km]		*M*		*R* [km]		*M*		*R* [km]	
		Ex.	Occ.	Ex.	Occ.	Ex.	Occ.	Ex.	Occ.	Ex.	Occ.	Ex.	Occ.
Tauranga	25	6.2	6.0	94	101	6.3	6.2	96	108	6.7	6.5	126	136
	100	6.4	6.3	88	91	6.5	6.4	83	90	6.9	6.8	110	123
	500	6.6	6.5	85	85	6.6	6.5	76	79	7.0	6.9	90	103
	2500	6.8	6.7	87	85	6.8	6.7	71	73	7.0	7.0	70	81
Timaru	25	6.3	6.2	91	111	6.6	6.4	116	137	6.9	6.7	161	174
	100	6.4	6.4	65	83	6.8	6.7	90	107	7.3	7.1	140	155
	500	6.2	6.3	39	53	6.8	6.8	66	80	7.5	7.4	120	131
	2500	6.1	6.1	23	29	6.6	6.7	44	57	7.7	7.7	106	113
Wanaka	25	6.2	6.1	56	69	6.5	6.3	70	85	6.9	6.6	109	125
	100	6.3	6.3	42	51	6.6	6.6	53	63	7.2	7.0	85	103
	500	6.3	6.3	30	37	6.7	6.7	39	48	7.4	7.4	60	74
	2500	6.4	6.3	19	25	6.7	6.7	23	34	7.3	7.5	39	54
Wellington	25	6.5	6.2	51	61	6.7	6.4	55	68	7.0	6.8	73	99
	100	7.0	6.6	35	48	7.2	6.9	35	50	7.4	7.2	37	60
	500	7.6	7.3	20	23	7.7	7.5	17	20	7.6	7.6	14	20
	2500	7.9	7.7	20	18	7.9	7.8	17	16	7.5	7.6	10	11
Whakatāne	25	6.3	6.1	47	55	6.4	6.3	44	57	6.6	6.5	48	74
	100	6.4	6.3	40	42	6.6	6.5	32	37	6.7	6.6	25	34
	500	6.7	6.5	40	39	6.8	6.7	28	30	6.8	6.7	16	19
	2500	7.0	6.8	44	40	7.1	6.9	26	28	7.0	6.9	10	13
Whanganui	25	6.3	6.1	71	77	6.5	6.3	76	86	6.9	6.7	107	122
	100	6.6	6.3	67	67	6.8	6.5	65	69	7.2	7.0	86	101
	500	7.1	6.8	71	67	7.3	6.9	65	62	7.5	7.3	68	76
	2500	7.6	7.3	77	74	7.8	7.5	70	67	7.8	7.6	62	62
Whangārei	25	5.7	5.7	126	166	5.9	5.7	148	176	6.0	5.7	178	190
	100	5.8	5.8	77	106	6.0	5.9	107	137	6.3	6.1	160	176
	500	5.8	5.8	42	57	6.0	6.0	63	86	6.5	6.4	131	153
	2500	5.8	5.8	26	32	6.0	6.0	36	47	6.5	6.5	92	118