Seismic Hazard Assessment for the Proposed Waimea Dam

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EXECUTIVE SUMMARY

Acceleration response spectra for 5% damping have been estimated for Waimea Dam for NZS1170.5 Site Class B Rock site conditions, with an assumed average shear-wave velocity Vs30 over the top 30 metres of 800m/s, as assigned for this site class by Bradley (2013). The study differs from the earlier study of Buxton et al. (2011) by incorporating an updated seismicity model, including modelling of the Waimea Fault as three rather than two source segments, and by using the weighted combination of five ground-motion prediction equations (GMPEs) rather than the one used in 2011.

The five ground-motion prediction equations used are: the New Zealand models of McVerry et al. (2006) and Bradley (2013), and three models from the NGA-West 2014 GMPE study, namely Abrahamson, Silva & Kamai (ASK, 2014;) Boore, Stewart, Seyhan and Atkinson (BSSA, 2014); and Campbell & Bozorgnia (CB, 2014). The weights for each of the models were: ASK 1/6; BSSA 1/6; CB 1/6; Bradley 3/10 and McVerry 2/10. The McVerry model characterises site conditions through the NZS1170 site classes, while the other models use Vs30.

Probabilistic spectra have been estimated for return periods of 150, 500, 2500 and 10,000 years. Deterministic spectra for various rupture scenarios have also been produced, including considering multi-fault ruptures (combined Waimea Central and South fault segments, combined Waimea South and Alpine Kaniere-Tophouse source, and combined Wairau and Alpine Kaniere-Tophouse source).

Tables ES1 and ES2 respectively list the probabilistic mean and 84-percentile estimates of the 5% damped acceleration response spectra for the four return periods. The results are given both unweighted (UW) and with magnitude-weighting (MW) up to periods of 0.5s. The weighting for magnitude M is (M/7.5)1.285, as used in developing the spectra of NZS1170.5:2004. The values are for RotD50 (very similar to the geometric mean) versions of the GMPEs. Hanging wall factors have been incorporated in all the GMPEs. The NZSOLD Large Dam Guidelines require the mean estimate of the 10,000-year spectrum for the Safety Evaluation Earthquake (SEE) motions, if they are determined probabilistically.

Figures ES1 and ES2 show the mean unweighted spectra on linear and log-log plots. These figures also show the mean spectra for the case where the average recurrence interval of the southern segment of the Waimea Fault has been reduced from 5600 years to 4000 years, in recognition of the possibility that the slip rate of the Waimea Fault increases towards the south as it becomes closer to the higher strain-rate Wairau and Alpine faults. The effect of this change on the hazard estimates is slight, a maximum of less than 2% at the peak of the 10,000-year spectrum, and generally much less than that.

Figures ES3 and ES4 indicate the variation of results between the GMPEs by showing the probabilistic 50- and 84-percentile unweighted spectra across the GMPEs, as well as the mean spectra shown in Figures ES1 and ES2. The 50-percentile spectra are very similar to the mean spectra listed in Table ES1, and are virtually indistinguishable from them in the plots, except at long spectral periods and return periods.

Figures ES5 and ES6 compare the unweighted and magnitude-weighted spectra, on linear and log scales. Magnitude-weighting generally has only minor effects on these spectra, with the largest effects at the peaks of the spectra, which are reduced by about amounts ranging from about 15% for the 150-year spectrum down to about 4% for the 10,000-year spectrum.

Spectra for three multi-segment fault-rupture scenarios have been considered as alternatives to the mean 10,000-year spectrum for the Safety Evaluation Earthquake (SEE) motions. The scenarios considered were: combined rupture of the central and southern segments of the Waimea Fault in a magnitude 7.5 earthquake at a shortest distance of about 8 km from the dam site; combined rupture of the Waimea South and Alpine sources in a magnitude 7.8 earthquake at a shortest distance of about 12 km from the dam site; and combined rupture of the Wairau and Alpine Faults in a magnitude 8.3 earthquake at about 21 km shortest distance. The mean 50th- and 84th-percentile estimates of these scenario spectra are shown in Figures ES7 and ES8, in linear and log plots. The spectra are the weighted combination of the 5 ground-motion prediction equations considered. Also shown are the mean uniform hazard spectra for return periods of 150, 500, 2500 and 10,000 years. None of these spectra are magnitude-weighted. The 84th-percentile scenario spectra range from around the 2500-year motions to stronger than the 10,000-year motions. The strongest 84th-percentile scenario estimates, for the combined rupture of the central and south segments of the Waimea Fault, exceed the mean 10,000-year spectrum, so need not be considered for the SEE motions according to the NZSOLD (2015) Guidelines. The recommended SEE spectrum is the mean 10,000-year spectrum (Table ES3). The mean estimate of the 84th-percentile motions for the combined Alpine-Waimea South sources is very similar to the 10,000-year probabilistically-based SEE spectrum.

Figure ES9 shows that the probabilistic spectra estimated in the current study are considerably reduced from those of the 2011 study. The change appears to result mainly from the seismicity model rather than the use of a combinations of GMPEs in place of the single one used in 2011.

The main contribution (about 60% of the total) to the exceedance rate of the 10,000-year spectrum is from the central and south segments of the Waimea Fault, modelled as producing magnitude 7.1 earthquakes at distances of 8 km and 12 km, respectively, from the dam site, with average recurrence intervals of rupture of about 6000 years for both sources. The contribution-averaged magnitude for the 10,000-year peak ground accelerations is 7.2, because of the contributions of larger magnitude sources in addition to those of the Waimea Fault.

The recommended aftershock spectrum (Table ES4 and Figure ES10) corresponds to the 84th-percentile spectrum for a magnitude 6.8 earthquake at 12 km distance from the dam site, following a magnitude 7.8 main-shock corresponding to a combined rupture of the Alpine Kaniere-Tophouse and Waimea South fault segments. This is consistent with the 84th-percentile main-shock spectrum being similar to the probabilistic 10,000-year SEE spectrum.

Table ES 1 Summary of mean estimates of 5% damped unweighted (UW) and magnitude-weighted (MW) acceleration response spectra for Waimea dam for preferred fault source parameters.

Period T(s)	Mean 5% damped acceleration response spectra SA(T) (g)							
	Return Period							
	150yrs		500yrs		2500yrs		10,000yrs	
	UW	MW	UW	MW	UW	MW	UW	MW
0	0.15	0.13	0.25	0.22	0.42	0.40	0.64	0.62
0.075	0.29	0.24	0.47	0.40	0.82	0.75	1.26	1.18
0.1	0.34	0.28	0.55	0.48	0.99	0.90	1.52	1.44
0.15	0.36	0.31	0.59	0.53	1.06	0.99	1.65	1.58
0.2	0.36	0.31	0.59	0.53	1.04	0.99	1.61	1.55
0.25	0.32	0.28	0.52	0.48	0.91	0.88	1.40	1.36
0.3	0.29	0.26	0.47	0.44	0.82	0.80	1.25	1.23
0.35	0.26	0.24	0.42	0.40	0.75	0.74	1.14	1.13
0.4	0.24	0.22	0.38	0.37	0.68	0.67	1.04	1.04
0.5	0.20	0.18	0.33	0.32	0.58	0.59	0.90	0.91
0.75	0.14		0.24		0.43		0.67	
1	0.11		0.19		0.34		0.53	
1.5	0.081		0.13		0.25		0.38	
2	0.058		0.101		0.18		0.28	
3	0.036		0.066		0.12		0.19	

Table ES 2 Summary of 84-percentile estimates of 5% damped unweighted (UW) and magnitude-weighted (MW) acceleration response spectra for Waimea dam for preferred fault source parameters.

Period T(s)	84-percentile 5% damped acceleration response spectra SA(T) (g)							
	Return Period							
	150yrs		500yrs		2500yrs		10,000yrs	
	UW	MW	UW	MW	UW	MW	UW	MW
0	0.17	0.14	0.27	0.24	0.46	0.45	0.69	0.69
0.075	0.32	0.26	0.52	0.44	0.91	0.82	1.39	1.28
0.1	0.38	0.32	0.62	0.53	1.09	0.99	1.66	1.58
0.15	0.41	0.34	0.65	0.57	1.14	1.09	1.79	1.71
0.2	0.42	0.36	0.66	0.60	1.17	1.11	1.86	1.76
0.25	0.36	0.32	0.56	0.53	0.98	0.94	1.49	1.46
0.3	0.32	0.29	0.51	0.47	0.88	0.85	1.36	1.32
0.35	0.29	0.26	0.46	0.44	0.81	0.78	1.25	1.22
0.4	0.26	0.24	0.42	0.40	0.74	0.72	1.14	1.12
0.5	0.23	0.21	0.36	0.35	0.64	0.64	0.99	1.00
0.75	0.17		0.27		0.48		0.77	
1	0.13		0.21		0.38		0.60	
1.5	0.11		0.17		0.30		0.44	
2	0.083		0.13		0.22		0.33	
3	0.059		0.099		0.17		0.26	

Table ES 3 Summary of mean estimates of 5% damped unweighted acceleration response spectra for Waimea dam for a return period of 10,000 years and for the 84th-percentile spectra for three multi-segment fault-rupture scenarios. The 10,000-year spectrum is recommended from these candidates for the SEE spectrum.

Period T(s)	Mean 5% damped acceleration response spectra SA(T) (g)			
	Return Period or Scenario			
	10,000yrs	Waimea Central and South 84th-percentile	Waimea South and Alpine 84th-percentile	Wairau and Alpine 84th-percentile
0	0.64	0.74	0.60	0.44
0.075	1.26	1.47	1.15	0.79
0.1	1.52	1.76	1.36	0.93
0.15	1.65	1.97	1.54	1.07
0.2	1.61	1.94	1.54	1.10
0.25	1.40	1.70	1.36	1.00
0.3	1.25	1.50	1.22	0.91
0.35	1.14	1.37	1.11	0.84
0.4	1.04	1.25	1.03	0.78
0.5	0.90	1.06	0.88	0.68
0.75	0.67	0.76	0.64	0.51
1	0.53	0.60	0.52	0.41
1.5	0.38	0.40	0.36	0.31
2	0.28	0.28	0.27	0.23
3	0.19	0.17	0.18	0.16

Table ES 4 Recommended aftershock spectrum for a magnitude M6.8 Waimea South and Alpine Fault event, consistent with the associated magnitude 7.8 main-shock spectrum being similar to the10,000-year SEE spectrum.

Period T(s)	M6.8 Waimea South and Alpine aftershock spectrum SA(T) (g)
0	0.44
0.075	0.88
0.1	1.05
0.15	1.16
0.2	1.13
0.25	0.99
0.3	0.87
0.35	0.78
0.4	0.71
0.5	0.60
0.75	0.42
1	0.32
1.5	0.21
2	0.14
3	0.087

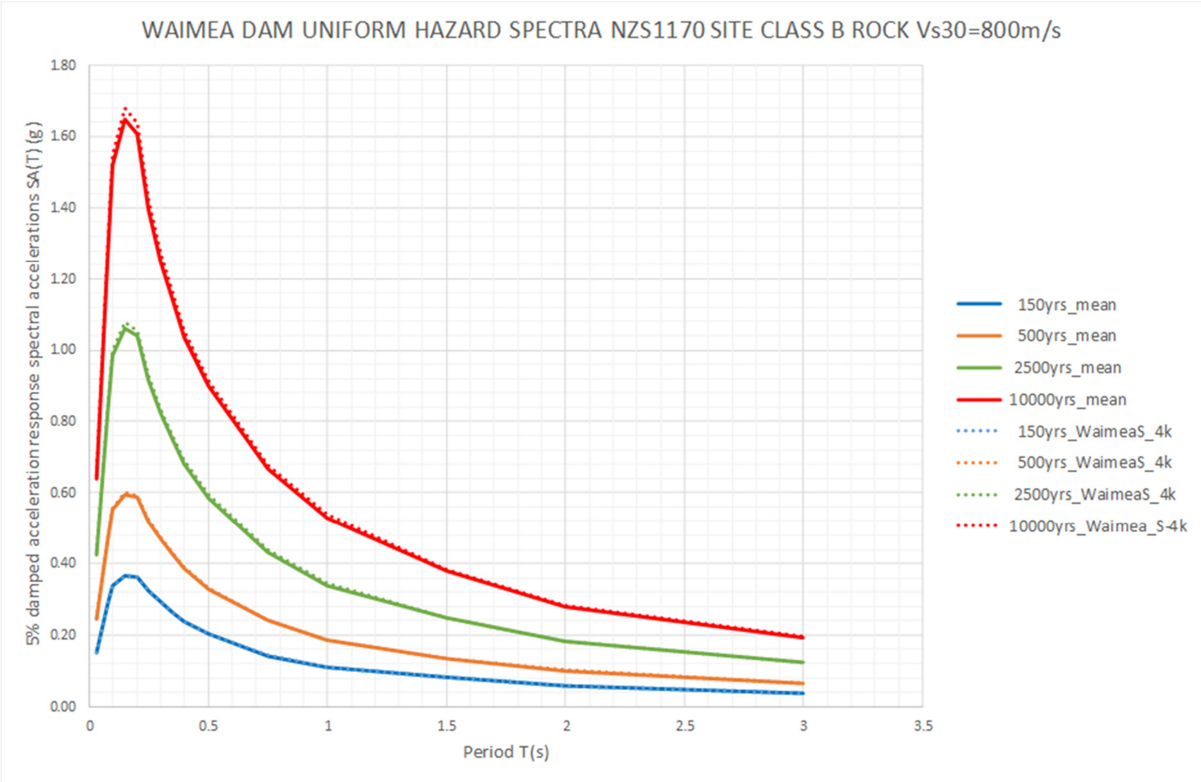

Figure ES 1 Waimea Dam mean 5% damped acceleration response spectra for return periods of 150, 500, 2500 and 10,000 years for preferred fault source model and model with shorter recurrence interval of 4000 years rather than 5600 years for the Waimea South fault source. There is no magnitude-weighting.

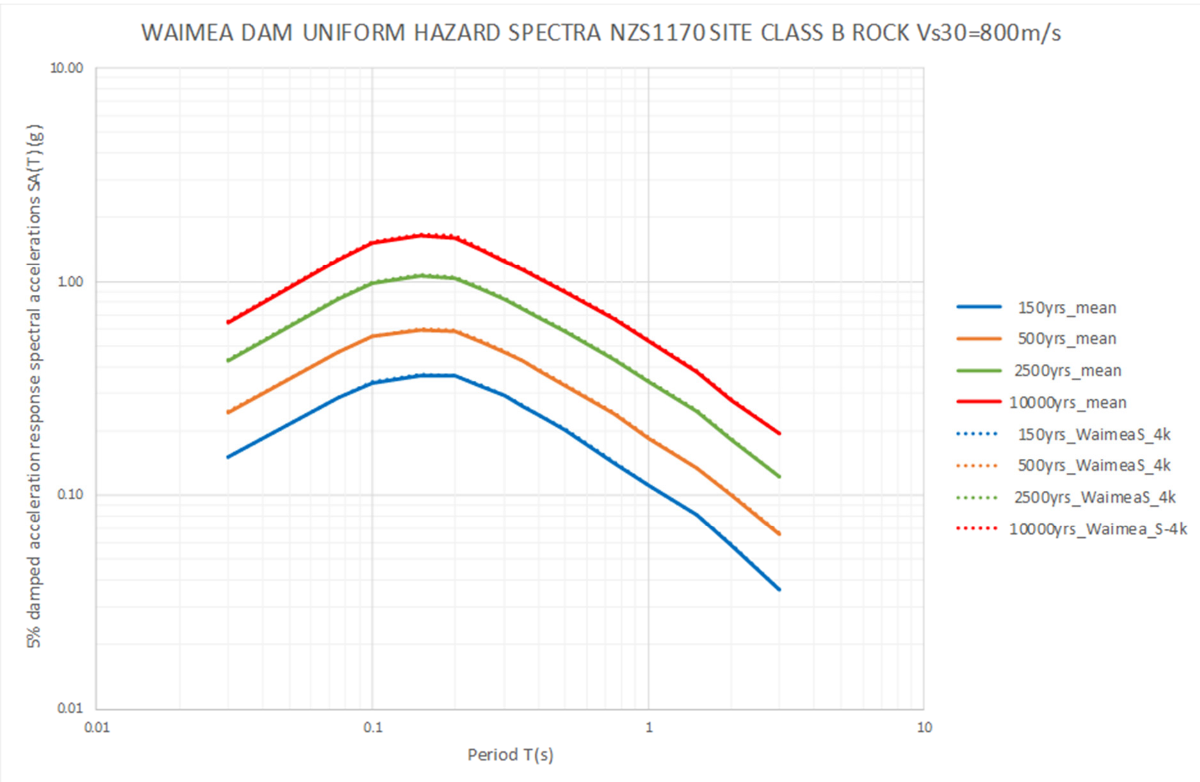

Figure ES 2 Spectra of Figure 1 on log-log plot.

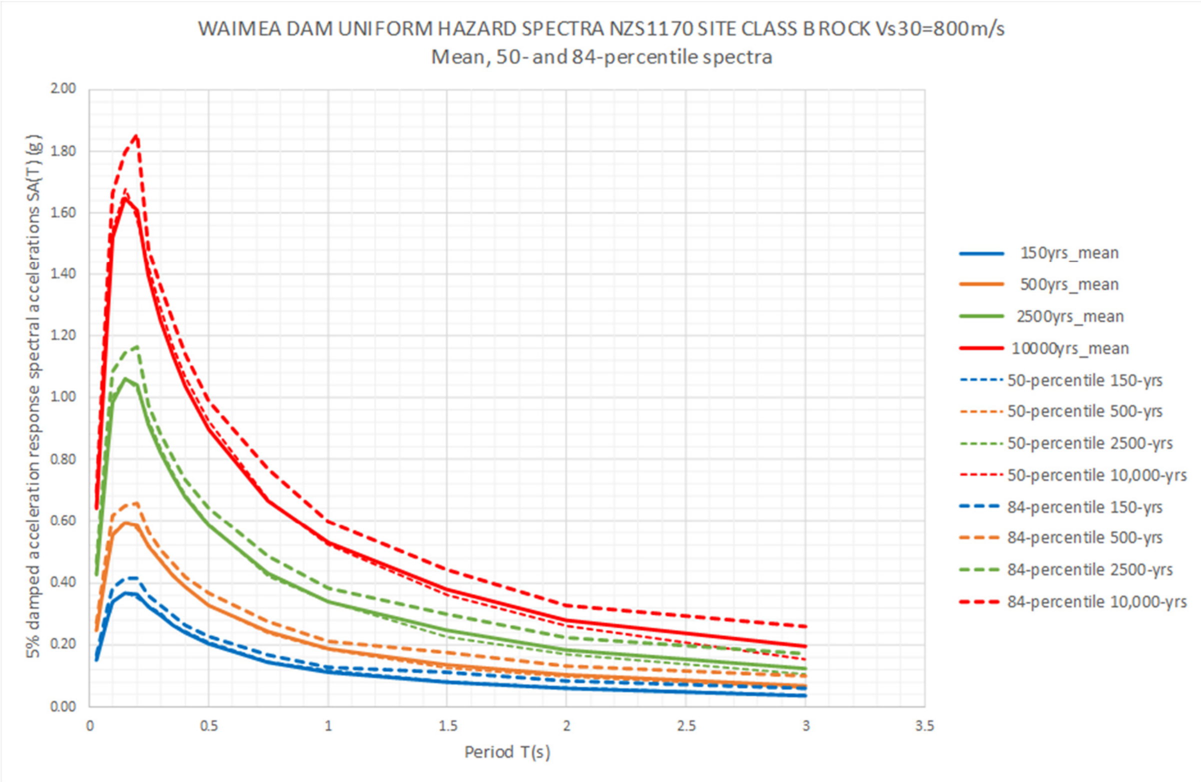

Figure ES 3 Mean spectra of Figure 1 for the preferred fault source model with the addition of the 50- and 84-percentile spectra for the weighted combination of all the GMPEs.

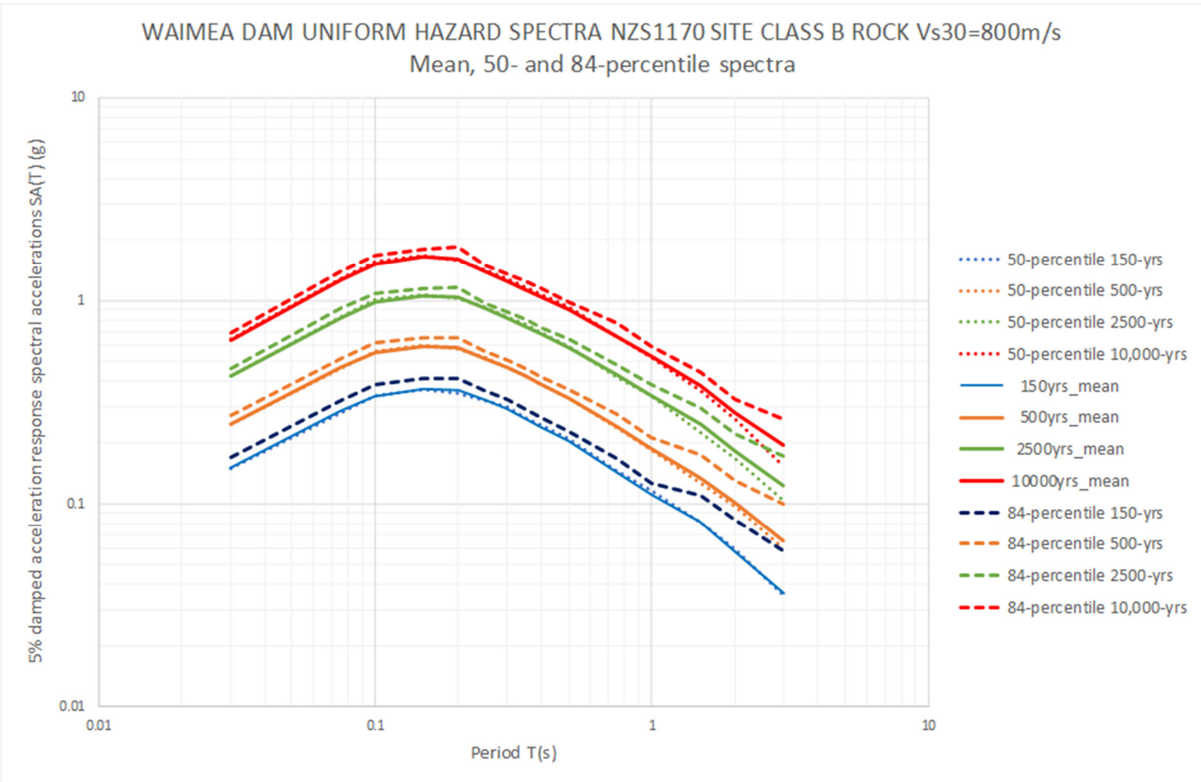

Figure ES 4 Spectra of Figure 3 on log-log plot.

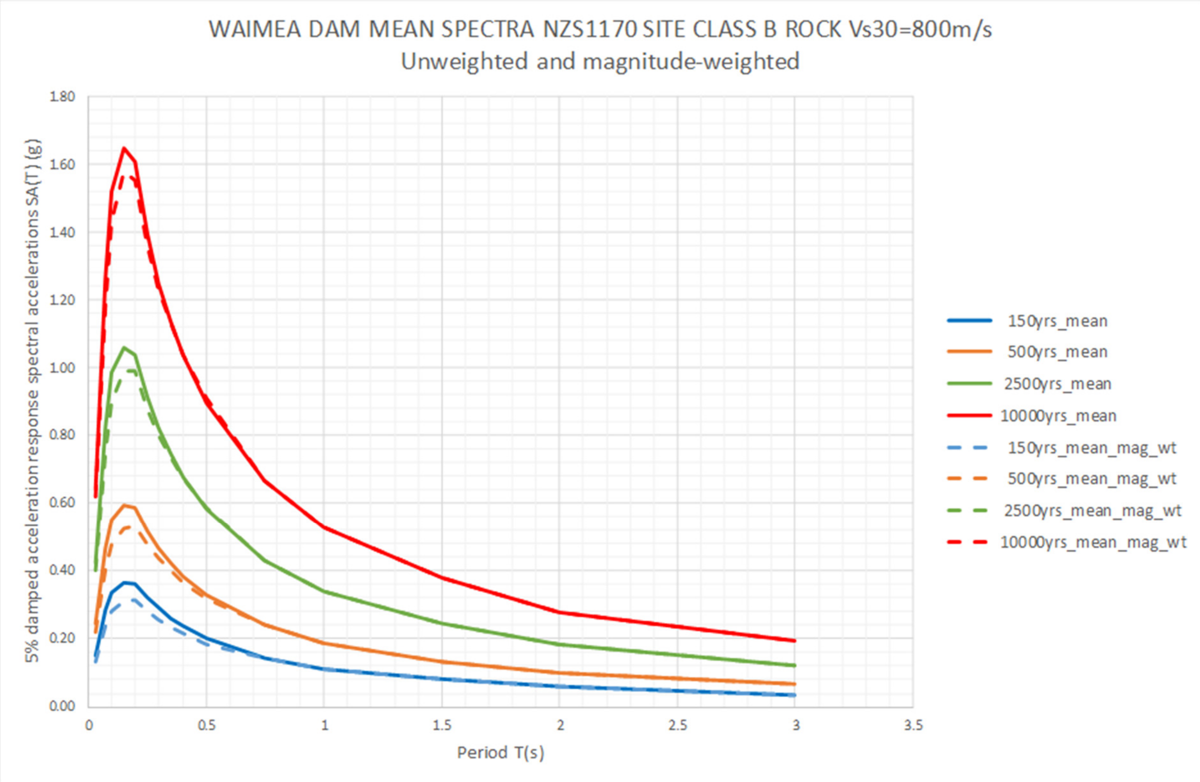

Figure ES 5 Waimea Dam mean spectra and mean magnitude-weighted spectra for return periods of 150, 500, 2500 and 10,000 years for the preferred fault source model.

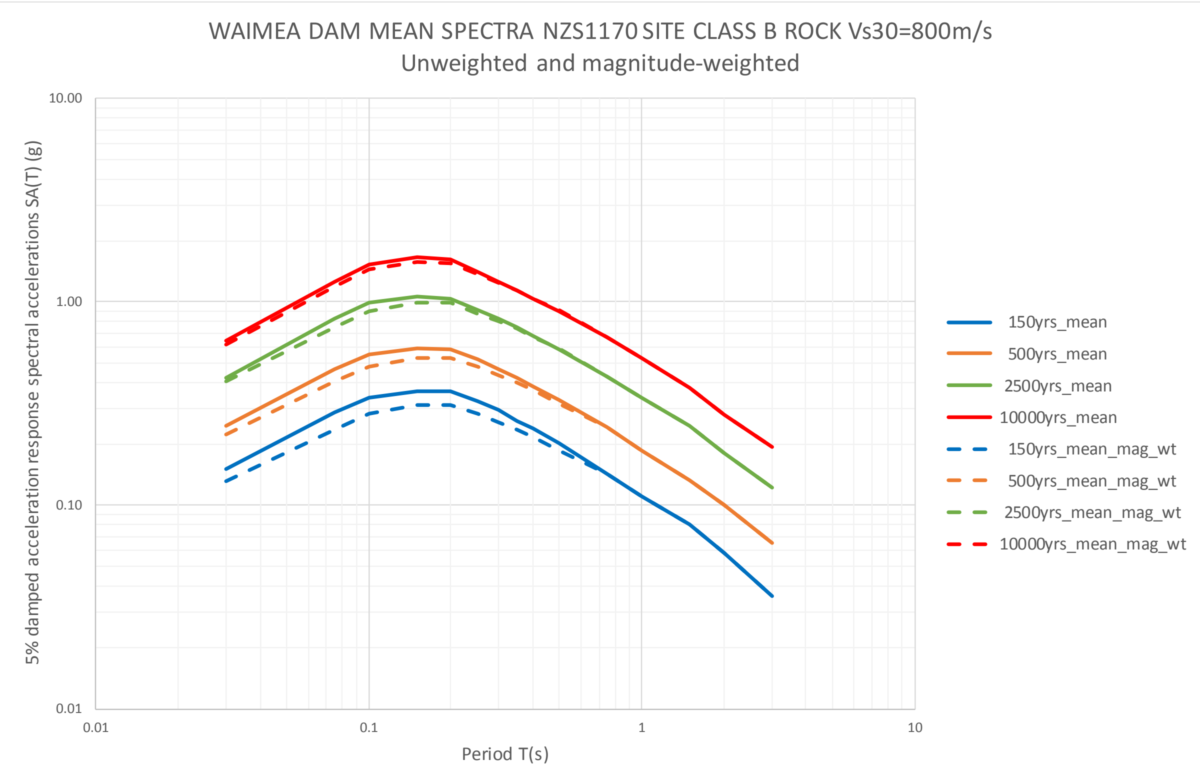

Figure ES 6 Spectra of Figure 5 on log-log plot.

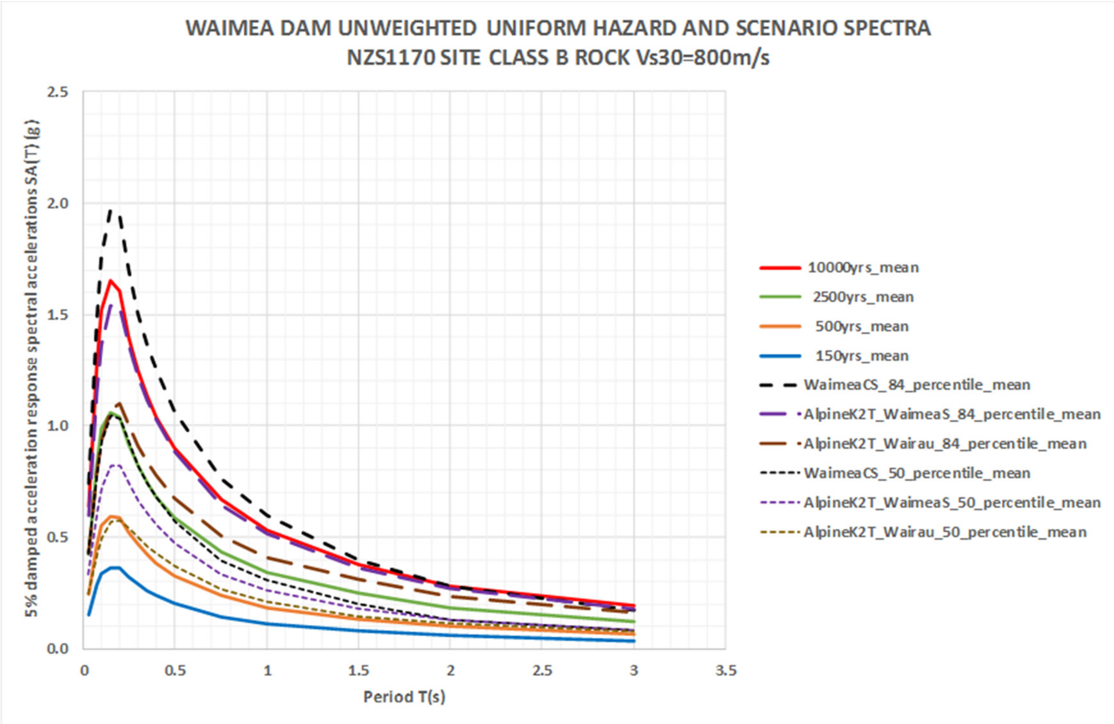

Figure ES 7 Comparison of mean uniform hazard spectra of Figure 1 with the mean estimates (over the 5 GMPEs) of the 50th - and 84th -percentile spectra for three multi-segment rupture scenarios. Magnitude-weighting is not included for any of the spectra. The mean 10,000-year spectrum is very similar to the mean estimate of the 84th-percentile motions for the combined Alpine-Waimea South sources. The strongest 84th-percentile scenario estimates, for the combined rupture of the central and south segments of the Waimea Fault, exceed the mean 10,000-year spectrum, so need not be considered for the SEE motions according to the NZSOLD (2015) Guidelines.

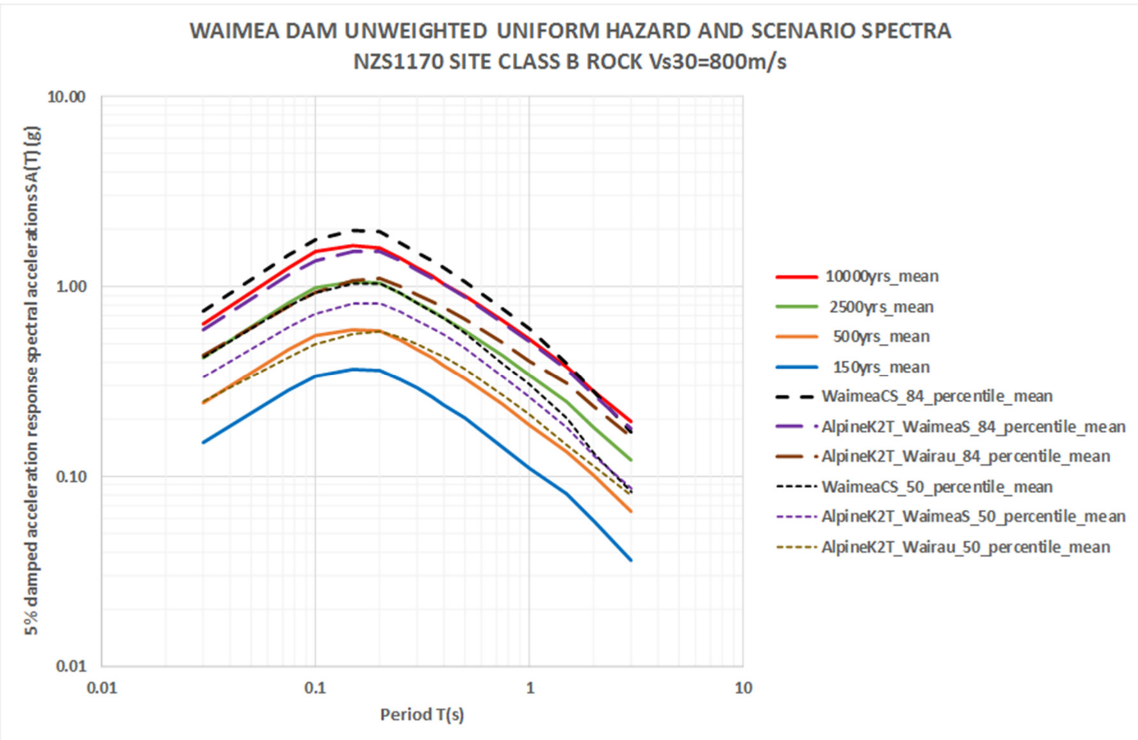

Figure ES 8 Spectra of Figure 7 on a log-log plot.

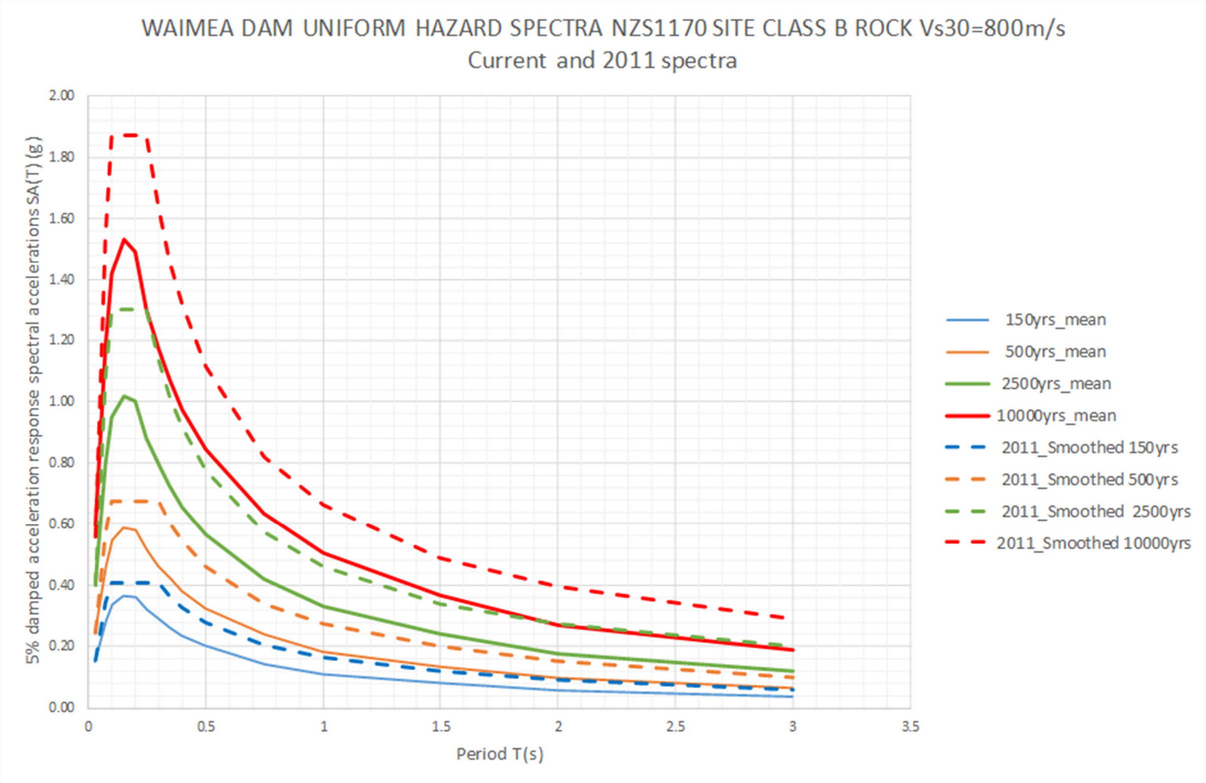

Figure ES 9 Comparison of the probabilistic spectra from the current study (solid curves) with those from the 2011 study (dashed curves).

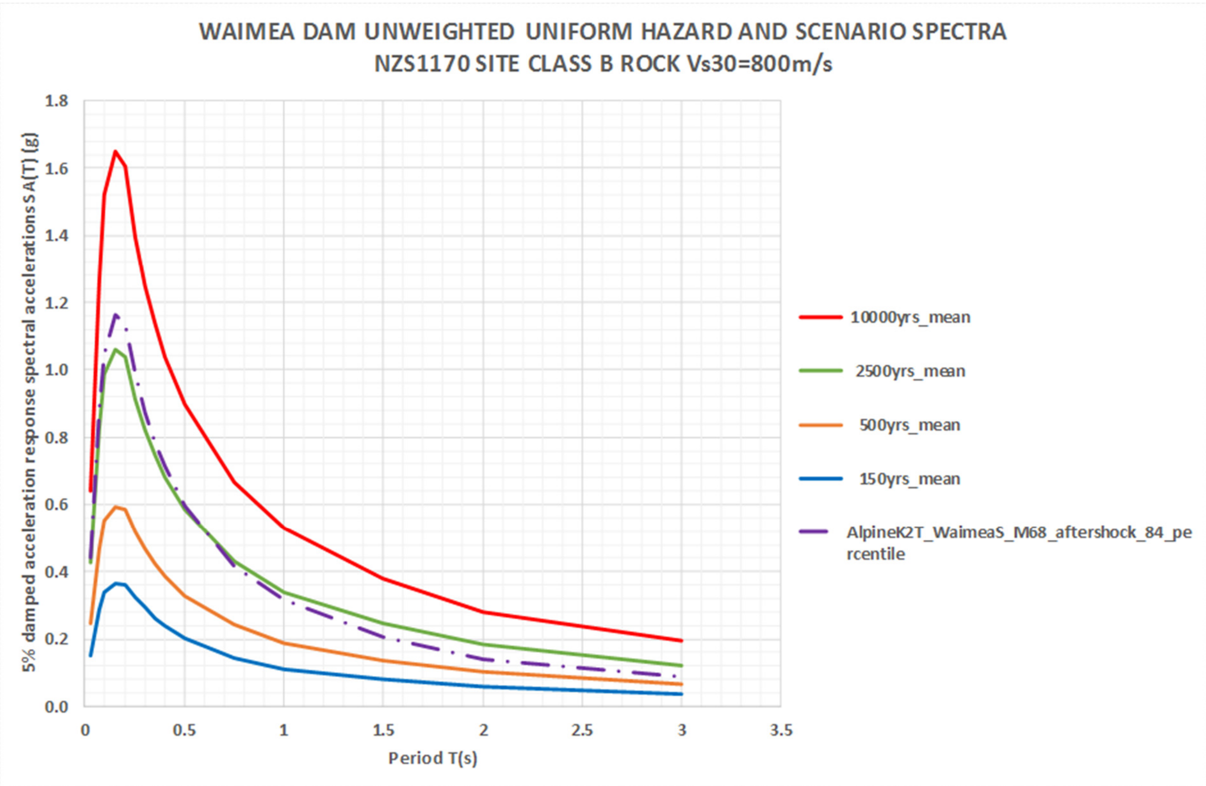

Figure ES 10 Recommended aftershock spectrum (dash-dot curves), for a magnitude 6.8 event following a magnitude 7.8 earthquake associated with combined rupture of the Alpine Kaniere-Tophouse and Waimea South fault segments, compared to the probabilistic spectra.

1.0 INTRODUCTION

1.1 TECHNICAL BRIEF

GNS Science was requested by Tonkin & Taylor Ltd on behalf of their client Tasman District Council to prepare an update of a site-specific hazard assessment for the Waimea (previously Lee Valley) Dam (GNS Science Consultancy Report 2011/26) to address the following issues: 1) Aftershock motions; 2) Findings from the Kaikoura and Canterbury earthquakes; 3) Outcomes from the resource consent process; and 4) Update due to the new NZSOLD guidelines.

The proposal stated:

'*Both magnitude-weighted and unweighted 5% damped acceleration response spectra and peak ground accelerations will be developed for horizontal motions for NZS1170.5 Class B Rock at the site of the proposed Waimea Dam, to satisfy the requirements of the 2015 NZSOLD New Zealand Dam Safety Guidelines (NZSOLD, 2015). Spectra will be produced for periods up to 3s. Results will be provided for return periods of 150, 500, 2500 and 10,000 years, together with deaggregations for the 10,000-year motions. The 150-year return period is appropriate for Operating Basis Earthquake (OBE) motions and the 10,000-year return period for the Safety Evaluation Earthquake (SEE) motions, if determined probabilistically, according to the NZSOLD Guidelines. The 500- and 2500-year motions satisfy the Ultimate Limit State requirements for Importance Level 2 (IL2) and IL4 structures on the site governed by the New Zealand structural design standard NZS1170.5:2004. Additionally, the 10,000-year return period motions will be compared with the strongest 84-percentile scenario motions for the controlling maximum earthquake (CME) (likely to be one of the segments of the Waimea Fault) and, if applicable, other key faults in the region. A simple deterministic approach will be used to estimate aftershock spectra, based on events one magnitude unit lower than the CME*.

The results will be a major update of those provided in the GNS Science Consultancy report 2011/26 (Buxton, McVerry and Van Dissen, 2011). The need for the major update results from a change between the 2000 and 2015 NZSOLD Guidelines, namely the requirement that 'Epistemic uncertainties associated with earthquake sources and ground motion prediction equations should be considered.' In discussions with Tonkin & Taylor and their advisors, Ian Walsh of Opus and Trevor Matuschka of Engineering Geology Ltd, it was decided that the uncertainties will be considered through sensitivity studies rather than full logic tree analysis. Even with a sensitivity-analysis approach, the consideration of epistemic uncertainties represents a large increase in the calculations required compared to the 2000 Guidelines that were addressed in the 2011 study, requiring multiple representations of the main fault sources affecting the seismic hazard at the site, and the combination of results from multiple ground-motion prediction equations (GMPEs).

The 2011 study did not consider the estimation of vertical motions, and these have not been requested for the update.

The starting point for the modelling of the faults will be the 2010 National Seismic Hazard Model (NSHM), as published in Stirling et al. (2012), with modification from a two- to a three-segment representation of the Waimea Fault, as developed in the course of the resource consent process (e-mail 3 December 2014 from G. McVerry of GNS Science to M. Foley of Tonkin & Taylor). Uncertainties in fault parameters will be addressed by considering increased *and reduced values of the recurrence intervals and magnitudes of the Waimea North, Central and South fault segments, as well as preferred values, based on studies of the Waimea-Flaxmore fault system through to the present. In addition, consideration will be given to whether any additional earthquake sources are required to represent the Waimea-Flaxmore fault system, including taking into account information provided in Fraser et al. (2006) and Johnston and Nicol (2013).*

One of the lessons from the Kaikoura earthquake was the possibility of ruptures extending along multiple faults, either as a single large source or one source triggering ruptures of neighbouring faults in the course of its propagation. To address this possibility, the sensitivity studies will include the estimation scenario motions for combined ruptures of two or three segments of the Waimea Fault, or of the Alpine Fault in conjunction with the Wairau or Waimea Faults.

Ground-motion uncertainty will be addressed by considering the two GMPEs most commonly used in New Zealand, namely McVerry et al. (2006) and Bradley (2013), together with one of the GMPEs from NGA-West project (Gregor at al. 2014) commonly used in California. The final selection of GMPEs and their weightings will not be pre-ordained; rather, the basis of their selection will be reviewed by Trevor Matuschka (Engineering Geology Ltd) when that stage of the work is reached.'

In addition, it was agreed that the calculations are to be for the geometric-mean component, or the 50th-percentile orientation, which is close to the geometric mean, for the NGA models.

1.2 2015 *NEW ZEALAND DAM SAFETY GUIDELINES*

Since the preparation of the 2011 report (Buxton et al, 2011), *the New Zealand Dam Safety Guidelines* (NZSOLD, 2000) have been updated (NZSOLD, 2015).

The proposed Waimea Dam has a high Potential Impact Classification (PIC) according to the briefing information supplied by Tonkin & Taylor Limited. For high PIC Dams, the *2015 Guidelines* allow the Safety Evaluation Earthquake (SEE) motions to be either the probabilistically-derived mean 1 in 10,000 Annual Exceedance Probability (AEP) ground motions or the deterministic scenario motions at the 84th-percentile level for the Controlling Maximum Earthquake (CME). The scenario motions need not exceed those derived by the probabilistic approach. The CME is defined as 'the maximum earthquake on a seismic source that is capable of inducing the largest seismic demand on a dam.' The *2015 Guidelines* also require that 'epistemic uncertainties associated with earthquake sources and ground motion prediction equations should be considered'.

The SEE requirements of the *2015 Guidelines* for high PIC dams are similar to the 2000 requirements, but are more onerous in two ways. The less important change is that the 2015 Guidelines specify the 84th-percentile level for the scenario motions, where the percentile level was previously undefined, although the 84th-percentile level was recommended in the Mejia et al. (2001) paper that was often used to interpret the *2000 Guidelines*. The effects of this change are limited by the retention of the maximum requirement in terms of the 1 in 10,000 AEP motions. Of more consequence is the new requirement to explicitly consider 'epistemic uncertainties', needing consideration of multiple GMPEs and multiple representations of the earthquake sources.

Although 'epistemic uncertainties' aren't defined in the *Guidelines*, they correspond to one of two items discussed in the description for uncertainty in the Glossary to the *Guidelines*:

‘**Uncertainty** – Result of imperfect knowledge concerning the present or future state of a system, event, situation or population under consideration. The level of uncertainty governs the confidence in predictions, inferences or conclusions. In the context of dam safety, uncertainty can be attributed to (i) inherent variability in natural properties and events, and (ii) incomplete knowledge of parameters and the relationships between input and output values.’

The first type of uncertainty above is often referred to as ‘aleatory’, and is accounted for in GMPEs by defining motions in terms of probabilistic distributions (usually log-normal distributions for PGAs or response spectral accelerations, defined in terms of their median values and the standard deviation of the logarithm of the acceleration). The second type of uncertainty is referred to as ‘epistemic’.

In this study, the requirements for considering epistemic uncertainties in GMPEs are addressed by the use of GMPE logic trees. Epistemic uncertainties in the fault locations, segmentation, parameters and the possibility of multi-segment ruptures are considered through sensitivity analyses and estimation of deterministic spectra for various fault-rupture scenarios as alternatives to the probabilistic hazard spectra. These two approaches were discussed in the proposal for this study and agreed to in the contract.

2.0 MODELLING OF EARTHQUAKE SOURCES

The starting point for the modelling of the earthquake sources in this study is the 2010 National Seismic Hazard Model (NSHM), as published in Stirling et al. (2012). The NSHM has two seismicity components: a 'distributed seismicity' component consisting of a three-dimensional grid of point sources that are not associated with specific faults, derived from the historical seismicity catalogue, and a geologically-based fault source component. The distributed seismicity component is unchanged from the 2010 NSHM. As specified in the proposal, the modelling of the fault sources is largely that of the 2010 NSHM, apart from modification of the representation of the Waimea Fault.

2.1 ACTIVE FAULT EARTHQUAKE SOURCES IN THE VICINITY OF THE WAIMEA DAM SITE

The modelling of the Waimea Fault has been modified from the two-segment representation of Stirling et al. (2012), as used in the 2011 hazard study for the site (Buxton et al., 2011), to a three-segment representation. The three-segment model was originally developed in the course of the 2014 resource consent process (e-mail 3 December 2014 from G. McVerry of GNS Science to M. Foley of Tonkin & Taylor). Slight changes to the original three-segment model of the Waimea Fault have been made in this study, with the dip of all three segments modified from the previous 90° to 70°, consistent with the value given by Johnston (1983), Fraser et al. (2006) and Johnston & Nicol (2013). This in turn has a small effect on the area of the rupture surface, and hence the estimated magnitudes and recurrence intervals. The parameters of the three segments of the Waimea Fault used in this study are listed in Table 2.1, together with those of the two other NSHM active fault earthquake sources most relevant to the Waimea Dam site, namely the Kaniere-Tophouse segment of the Alpine Fault (AlpineK2T) and the Wairau Fault. These parameters correspond to the current NSHM as updated since 2010. These and other nearby active fault sources of the NSHM are shown in Figure 2.1 The table also lists three combined sources. These are considered for generating deterministic spectra for multi-segment rupture scenarios (section 2.5), but not in the probabilistic hazard estimates.

2.2 WAIMEA-FLAXMORE FAULT SYSTEM

The closest known active fault, or fault system, to the Waimea Dam site is the Waimea-Flaxmore Fault System (e.g. Langridge et al. 2016). The Waimea-Flaxmore Fault System has an approximate length of 110-130 km, and extends from near St Arnaud in the southwest (where it intersects the Alpine Fault) to near D'Urville Island in the northeast. At its closest, it passes within about 8 to 9 km northwest from the Waimea Dam site. The Waimea-Flaxmore Fault System encompasses a number of active folds and faults (e.g. Waimea, Eighty-eight, Bishopdale, Flaxmore, Whangamoa faults) within a zone up to several kilometres wide (e.g., Johnston 1982, Rattenbury et al. 1998, Fraser et al. 2006, Johnson and Nicol 2013, Nicol et al. 2014). The multiple fault traces of this zone are modelled by a single through-going fault strand, with three lengthwise segments (Figure 2.1). The Waimea-Flaxmore Fault System spans active traces across 2 or 3 old terrane boundaries within the bedrock of the Waimea-Richmond Ranges. None of these terrane boundaries has a continuously mappable active fault trace along it, and, they are very closely spaced faults across strike. Therefore, it is assumed that collectively, the Waimea-Flaxmore Fault System could be represented by continuous rupture sources that involve multiple faults, or pieces of faults. Faults within the Waimea-Flaxmore Fault system typically have moderate to steep dips to the southeast, and predominantly a reverse sense of displacement with a subordinate, often minor, component of dextral strike-slip (e.g. Litchfield et al. 2014).

The Waimea-Flaxmore Fault System has not ruptured the ground surface and generated a large magnitude earthquake within written historic times. The timing of the most recent known rupture of the fault system, 400 to 1000 years ago, comes from an investigation trench site located about 20-25 km north from its intersection with the Alpine / Wairau Fault (Nicol et al. 2014). This southwestern portion of the fault system is termed WaimeaS (Waimea South) in the current National Seismic Hazard Model maintained by GNS Science. The next section of the Waimea-Flaxmore Fault System to the north is termed WaimeaC (Waimea Central), and it is the closest section to both Nelson City, and the Waimea Dam site. The paleoearthquake investigations of Fraser et al. (2006), south of Nelson city, indicate that this portion of the Waimea-Flaxmore Fault System last ruptured about 6,200 years ago, and has an average recurrence interval of surface fault rupture earthquakes of about 6,000 years (based on the timing of three surface fault rupture earthquakes over the last ~18,000 years which are presumed to be the three most recent ones). Comparatively less is known about the earthquake activity of the northeastern portion of the fault system, termed WaimeaN (Waimea North) but, for several reasons outlined in Johnston and Nicol (2013) and Nicol et al. (2014), its activity is presumed to be less than sections of the fault system further to the southwest that are closer to the higher strain-rate Alpine Fault and Marlborough Fault System.

All three sections of the Waimea-Flaxmore Fault System, as portrayed in the current National Seismic Hazard Model (WaimeaS, WaimeaC, and WaimeaN), are considered capable of generating earthquakes in the order on M 7 with average recurrence intervals of about 6000 years, based on considerations related to fault length and single-event displacement sizes of about 2.5 – 3.2 m of ground surface displacement per event.

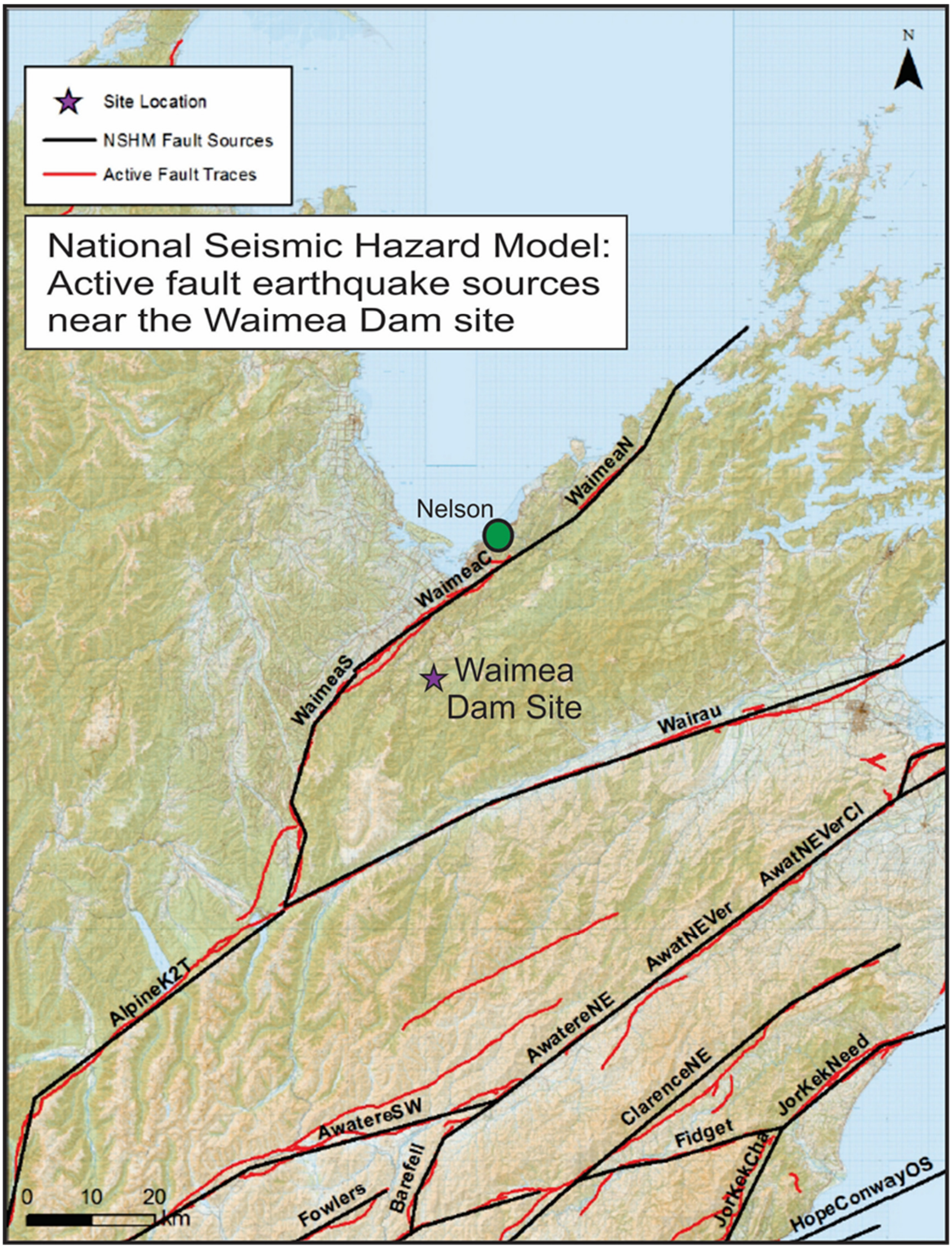

Figure 2.1 Characterisation of fault sources in the vicinity of the proposed Waimea Dam in the National Seismic Hazard Model (Stirling et al., 2010), with updating of the segmentation of the Waimea Fault.

Table 2.1 Earthquake parameters for active fault earthquake sources closest to the Waimea Dam site.

Active fault earthquake source	Type	Type Index	Length (km)	Dip (°)	Dip dir (°)	Depth (km)	SR (mm/yr)	M_w	SED (m)	RI (yrs)
WaimeaS	rs	3	40	70	110	12	0.5	7.1	2.8	5600
WaimeaC	rs	3	42	70	145	12	0.5	7.1	2.9	5800
WaimeaN	rs	3	40	70	130	12	0.5	7.1	2.8	5600
Wairau	ss	3	143	80	160	12	4	7.8	10.0	2500
AlpineKT	ss	1	194	60	145	12	7	7.7	4.3	620
WaimeaCS	rs	3	82	70	128	12	-	7.5	5.7	-
AlpineKT-WaimeaS	sr	1	234	60	110	12	-	7.8	-	-
AlpineKT-Wairau H&B scaling	ss	1	337	80	160	12	-	7.9	-	-

Type: rs= predominantly reverse fault with strike-slip component; ss = strike-slip fault; sr = predominantly strike-slip with reverse component.

Type Index: fault source empirical earthquake magnitude code for New Zealand crustal faults, Equations 1 and 3 in Stirling et al. (2012).

Length, Dip and Dip direction are average values calculated from mapped fault traces.

SR: estimates of the late Quaternary slip rate.

SED: single-event displacement, calculated from Equation 5 in Stirling et al. (2012).

RI: recurrence interval, calculated from Equation 4 in Stirling et al. (2012).

2.3 WAIRAU FAULT

The closest, short (<2500 yr) recurrence interval fault to the Waimea Dam site is the Wairau Fault, about 21 to 22 km south-southeast from the site, at its closest. The Wairau Fault is the northeastern section of the Alpine Fault, and extends from the Nelson Lakes area in the west-southwest to offshore Cook Strait in the east-northeast. Like the Waimea-Flaxmore Fault System, the Wairau Fault has not ruptured in a large earthquake within historic times. Paleoearthquake investigations on the Wairau Fault indicate that the fault has a recurrence interval of surface fault rupture earthquakes in the order of 2000 to 3000 years (e.g., Barnes & Pondard 2010, Zachariasen et al. 2006). Single-event surface rupture displacements of up to about 6 m have been documented on the fault, and this, along with its anticipated surface rupture length are consistent with the fault being capable of generating moderate to high magnitude 7 earthquakes. In the National Seismic Hazard Model, the Wairau Fault is modelled as a 143 km long, Mw 7.8 earthquake source with a recurrence interval of approximately 2500 years (Stirling et al. 2012).

2.4 ALPINE FAULT

The Alpine Fault is the longest and has the highest slip-rate of all on-land faults in New Zealand. The extent of the North Westland section of the Alpine Fault (Alpine K2T source) is defined by intersections with major faults: to the southeast by its intersection with the high slip-rate Hope Fault near Lake Kaniere, and to the northeast by its intersection with the Waimea-Flaxmore Fault System near Tophouse (e.g. Stirling et al. 2012, Howarth et al. 2014). In the National Seismic Hazard Model, the North Westland section of the Alpine Fault is modelled as a 194 km long, M 7.7 earthquake source with a recurrence interval of approximately 600 years, and it is called the Alpine Kaniere - Tophouse active fault earthquake source (AlpineK2T in

Figure 2.1) (Stirling et al. 2012). At its closest, the Alpine Kaniere - Tophouse source is about 40 - 45 km southwest from the Waimea Dam site.

2.5 SENSITIVITY STUDIES FOR FAULT MODELLING

In characterising active fault earthquake sources for the National Seismic Hazard Model, considerable effort goes into making sure modelled source parameters are consistent with known paleoearthquake data for the active faults those sources represent. However, high-quality paleoearthquake data are not available for all active faults. For example, much more is known about the activity of the southern and central sections of the Waimea-Flaxmore Fault System than the northern section. As a consequence, it is inevitable that assumptions have been made regarding the parameterisation of active fault earthquake sources in the National Seismic Hazard Model. In addition, recent large earthquakes in New Zealand, such as the 2010 Darfield earthquake and the 2016 Kaikoura earthquake, have shown that a specific earthquake can result from the rupture of multiple sections of the same fault, and can also be the result of rupture of multiple faults from differing tectonic provinces and with differing slip rates, and recurrence intervals (e.g. Hamling et al. 2017, Stirling et al. 2017).

With regards to the Waimea Dam site, it is important to understand what, if any, impact potential uncertainties in active fault earthquake source parameterisation may have on the evaluation of earthquake ground motions at the site. In this current study, we explore this topic through a series of four sensitivity scenarios (Figures 2.2 to 2.5). The specific uncertainties that are encompassed by these four scenarios are as follows:

1. The southwestern part of the Waimea-Flaxmore Fault System may be more active than the northeastern part.
2. A large earthquake impacting the Waimea Dam site may be the result of rupture of multiple sections of the same fault.
3. A large earthquake impacting the Waimea Dam site may involve rupture of multiple faults from differing tectonic provinces and with different slip rates and recurrence intervals.

2.5.1 Scenario 1: reduced recurrence interval for WaimeaS

In sensitivity scenario 1, the recurrence interval of the WaimeaS active fault earthquake source is arbitrarily reduced by a third (Figure 2.2). This scenario has the WaimeaS source rupturing with a recurrence interval of 4000 years (c.f. ~6000 years), and emulates the possibility that the southwestern part of the Waimea-Flaxmore Fault System is more active than the northeastern part, and has experienced 1 - 2 additional earthquakes over the last ~18,000 years compared to the northeastern part of the fault system (see item 1 above).This scenario is considered as an alternative in a sensitivity analysis for the probabilistic hazard estimates.

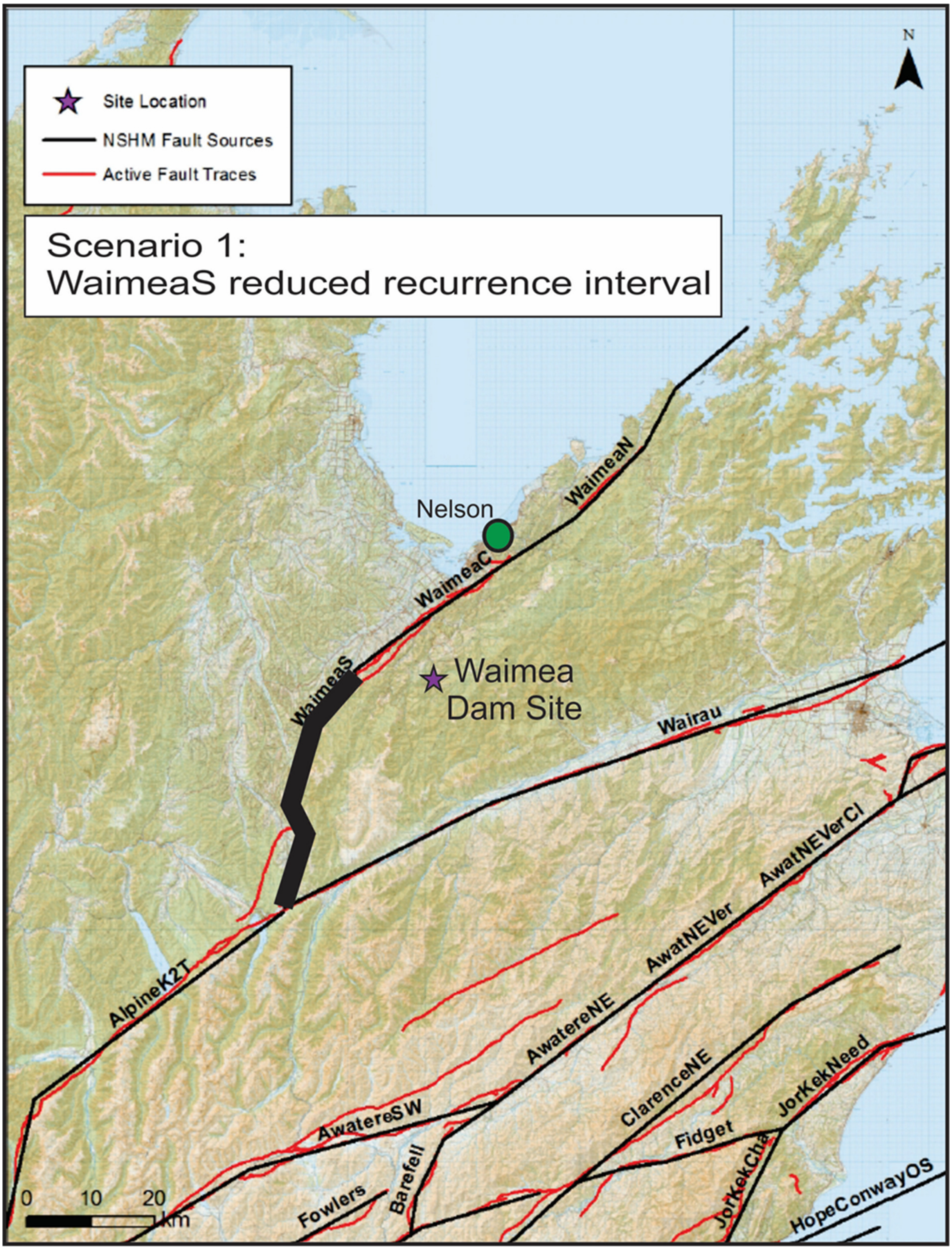

Figure 2.2 The bold lines indicate the Waimea South fault segment, for which the average recurrence interval of rupture was reduced from 5600 to 4000 years for re-estimation of the probabilistic spectra in the first of the sensitivity studies.

2.5.2 Scenario 2: combined rupture of WaimeaS and WaimeaC

Sensitivity scenario 2 involves the combined rupture of the WaimeaS and WaimeaC sources (Figure 2.3). This scenario implies an earthquake with a rupture length of about 82 km, a magnitude of M 7.5, and a source to site distance of 8 – 9 km. This scenario provides insight into the potential impact on ground motion evaluation at the Waimea Dam site of uncertainty item 2 above. It is considered in producing 50th- and 84th-percentile deterministic estimates of ground-motions at the proposed dam site, but not in probabilistic hazard estimates.

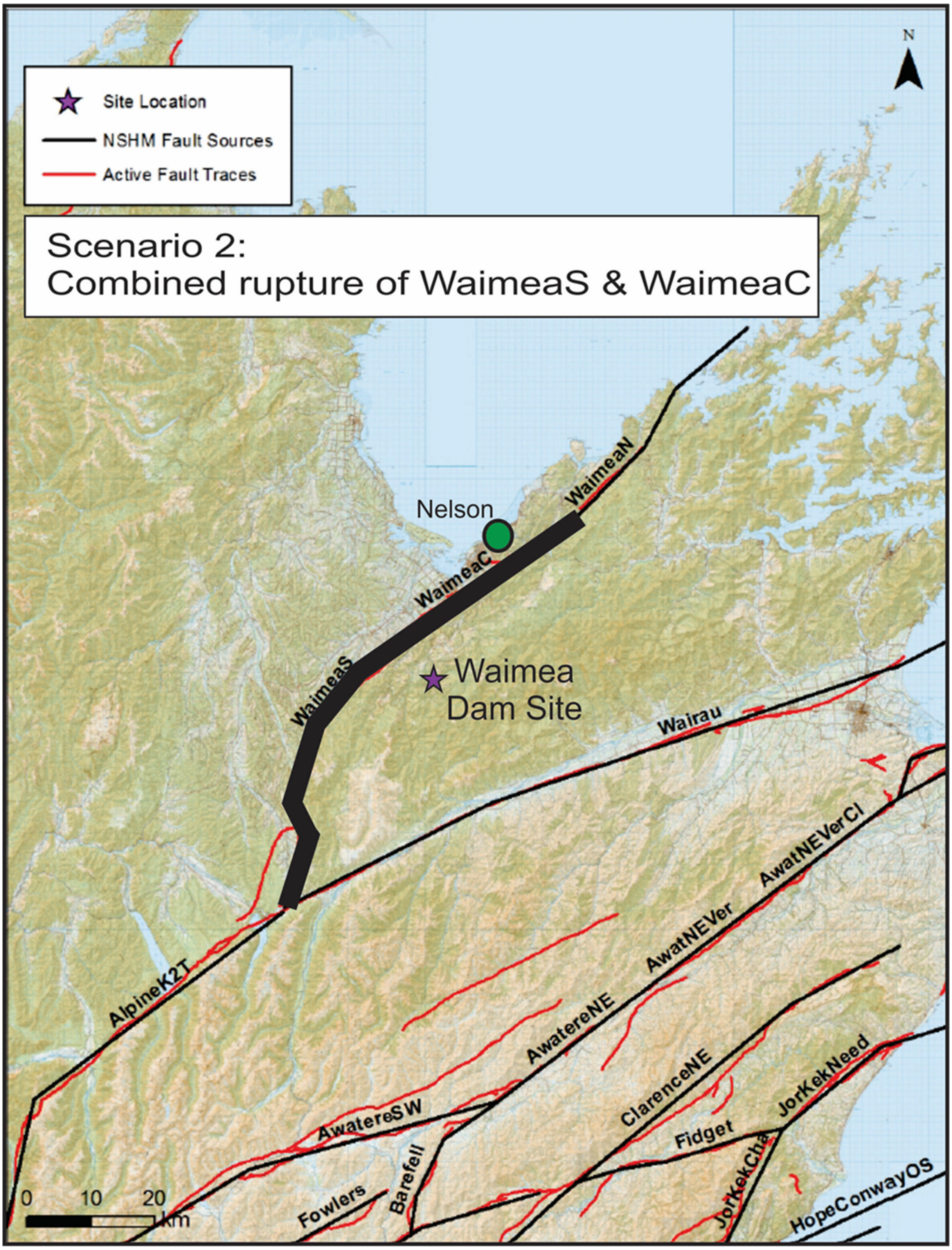

Figure 2.3 The bold lines indicate the combined Waimea South and Central fault segments, for which 50th- and 84th- percentile deterministic scenario spectra were estimated in the second of the sensitivity studies.

2.5.3 Scenario 3: combined rupture of AlpineK2T and WaimeaS

Sensitivity scenario 3 involves the combined rupture of the Alpine Kaniere-Tophouse active fault earthquake source (AlpineK2T) and the WaimeaS source (Figure 2.4). This scenario implies an earthquake with a rupture length of about 235 km, a magnitude of M 7.8, and a source to site distance of about 12 km. This scenario provides insight into the potential impact on ground motion evaluation at the Waimea Dam site of uncertainty items 1 and 3 above. It is considered to produce deterministic estimates of ground-motions at the proposed dam site, but not in probabilistic hazard estimates.

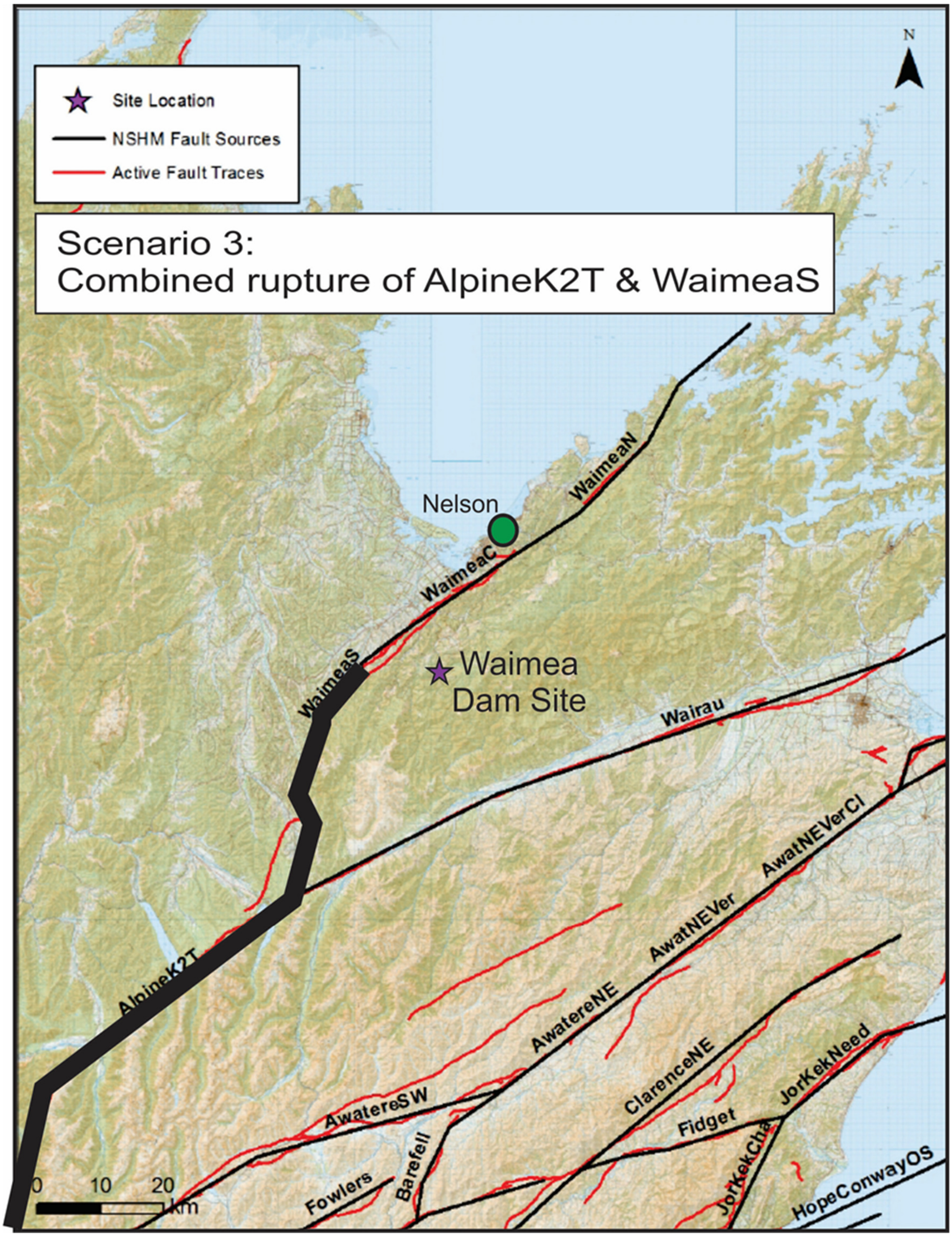

Figure 2.4 The bold lines indicate the combined Alpine Kaniere-Tophouse and Waimea South fault segments, for which 50th- and 84th- percentile deterministic scenario spectra were estimated in the third of the sensitivity studies.

2.5.4 Scenario 4: combined rupture of AlpineK2T and Wairau

Sensitivity scenario 4 involves the combined rupture of the AlpineK2T source and the Wairau source (Figure 2.5). This scenario implies an earthquake with a rupture length of about 340 km, a magnitude of M 7.9, and a source to site distance of about 22 – 23 km. This scenario provides insight into the potential impact on ground motion evaluation at the Waimea Dam site of uncertainty item 2 above. It is considered to produce deterministic estimates of ground-motions at the proposed dam site, but not in probabilistic hazard estimates.

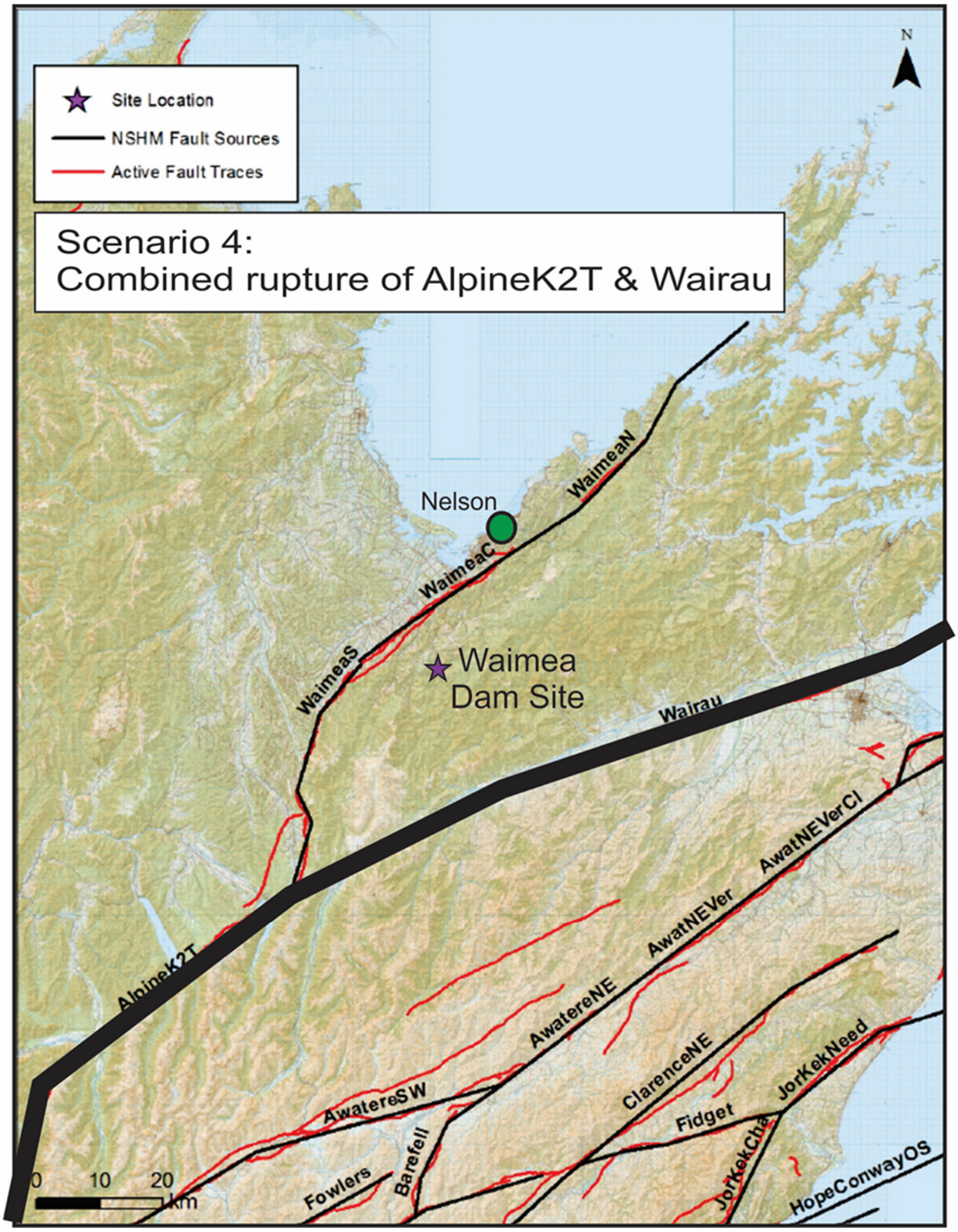

Figure 2.5 The bold lines indicate the combined Alpine Kaniere-Tophouse and Wairau fault segments, for which 50th- and 84th- percentile deterministic scenario spectra were estimated in the fourth of the sensitivity studies.

See Sections 4.2 and 4.4 of this report for detailed discussion regarding the potential impacts these four sensitivity scenarios have on the evaluation of probabilistic and deterministic scenario estimates of earthquake ground motions at the Waimea Dam site.

3.0 RECOMMENDATION OF GMPES FOR THE WAIMEA DAM STUDY

The contract for the Waimea Dam seismic hazard estimates calls for the use of three GMPEs, the McVerry et al. (2006) model, the Bradley (2013) model, and one of the models from the 2014 NGA-West-2 project (Gregor et al., 2014). The NGA-West-2 project produced five GMPEs, all summarised in the August 2014 issue of Earthquake Spectra (Volume 30, Number 3), namely: Abrahamson, Silva & Kamai (ASK); Boore, Stewart, Seyhan and Atkinson (BSSA); Campbell & Bozorgnia (CB); Chiou & Youngs (CY); and Idriss (2014). The Bradley (2013) model was derived from an earlier but similar version of the CY model (Chiou at al., 2010).

The various GMPEs were compared for several scenarios relevant to the Waimea Dam hazard study, based on the position of the dam relative to known faults and results of the 2011 analysis. These included a magnitude 7 oblique reverse mechanism earthquake at a shortest distance D of the dam from the Waimea Central fault segment of 8.3 km; a magnitude 7.8 oblique-reverse mechanism earthquake at distance D=12 km from the combined Waimea South/Alpine Kaniere-Tophouse sources; and magnitude 5.5 reverse and strike-slip mechanism earthquakes at a distance of 15 km to represent moderate magnitude local earthquakes not associated with known faults. These scenarios were chosen as representative of classes of events, or because they produce stronger motions than similar events at greater distances. For example, the Waimea North and Waimea South fault segments are associated with the same magnitude earthquakes as the Waimea Central segment, but at greater distances; the Waimea South/Alpine Kaniere-Tophouse source is associated with a larger magnitude event than the Waimea South segment at the same distance, or with a similar magnitude at shorter distance than the Wairau and Alpine Kaniere-Tophouse sources.

Observations from these scenario analyses are:

1. The NGA-West 2 GMPEs do not have separate spectra for reverse-oblique events. Predicted spectra for these models for this type of event are the same as for reverse mechanism events.
2. The Idriss spectra for the magnitude 7 and 7.8 scenarios exhibit shoulders in the period range starting at about 2s period (Figures 3.1 and 3.2), which are likely to be unrealistic; additional scenarios show that these shoulders occur for both strike-slip and reverse mechanisms; the incipient appearance of this feature starts at about magnitude 6.5, becoming more pronounced for larger magnitudes.
3. The Bradley and CY model from which it was derived provide very similar spectra (Figures 3.1 and 3.2).
4. The NGA West spectra often lie within quite narrow bands when plotted as a function of period, but exhibit different shapes.

In addition, the southern end of the Hikurangi subduction interface and the underlying slab produce earthquakes that may affect the dam site. Logic trees were also provided to consider subduction slab and interface GMPEs (see Section 3.2).

As part of the project discussions, it was agreed between Tonkin & Taylor and GNS Science that results are to be calculated for the geometric-mean horizontal component, or, for the NGA models, the 50th-percentile orientation, which is close to the geometric mean. The NGA-West 2 GMPEs were formulated in terms of these components. The McVerry et al. (2006) GMPEs contain expressions for both the larger and geometric-mean horizontal components.

3.1 HANGING WALL EFFECTS

The proposed Waimea Dam site is on the hanging wall of the Waimea Fault, i.e., on the side that lies above the dipping fault plane. This affects the strength of ground motions expected as a function of distance from the fault. A site on the hanging-wall side, particularly when it lies over the fault plane, will generally experience stronger motions from rupture of the fault than a site on the foot wall (the opposite side to the hanging wall) at the same shortest distance. This results from the hanging-wall site having a shorter average distance to the fault plane than the foot-wall site and from amplification effects as the wedge of material between the fault plane and surface tapers as the dipping fault approaches the surface. There is no tapering effect on the foot-wall side.

The NGA West-2 GMPEs, apart from the Idriss model, and the Bradley GMPE account for hanging-wall effects either through the choice of distance measure or through explicit hanging-wall factors. For the McVerry et al. (2006) GMPE, hanging-wall effects are accounted for in this study by adding the hanging-wall terms from the Abrahamson et al. (2014) GMPE, which in turn made use of simulation results of Donahue and Abrahamson (2014) and empirical fitting of data.

3.2 WEIGHTINGS OF THE INDIVIDUAL CRUSTAL GMPE MODELS

On the basis of these observations, it is recommended that the Idriss model be omitted because of poor behaviour at longer periods. The Bradley and CY spectra are largely duplicates of each other, so including the CY model together with the Bradley model is essentially including the same model twice. There appears no good reason for preferring any one of the ASK, BSSA or CB model over the other two. It is therefore recommended that they be given equal weighting.

The Expert Elicitation (EE) panel assembled by GNS Science after the Christchurch earthquake recommended a 60:40 weighting of the Bradley and McVerry GMPEs for magnitudes of 5.5 and greater (Gerstenberger et al., 2014). It is recommended that this relative weighting of these two models be retained in this study.

Finally, it is recommended that there be a 50:50 weighting of the combined NGA to the New Zealand models.

This leads to the recommended weights:

ASK 1/6; BSSA 1/6; CB 1/6; Bradley 3/10; and McVerry 2/10.

This selection of crustal GMPEs and weights was agreed to by reviewer Dr Trevor Matuschka (e-mail Trevor Matuschka of Engineering Geology Ltd to Graeme McVerry of GNS Science and Mark Taylor of Tonkin & Taylor Ltd, 27 June 2017) and Tonkin &Taylor (e-mail Mark Taylor to Graeme McVerry, 30 June 2017).

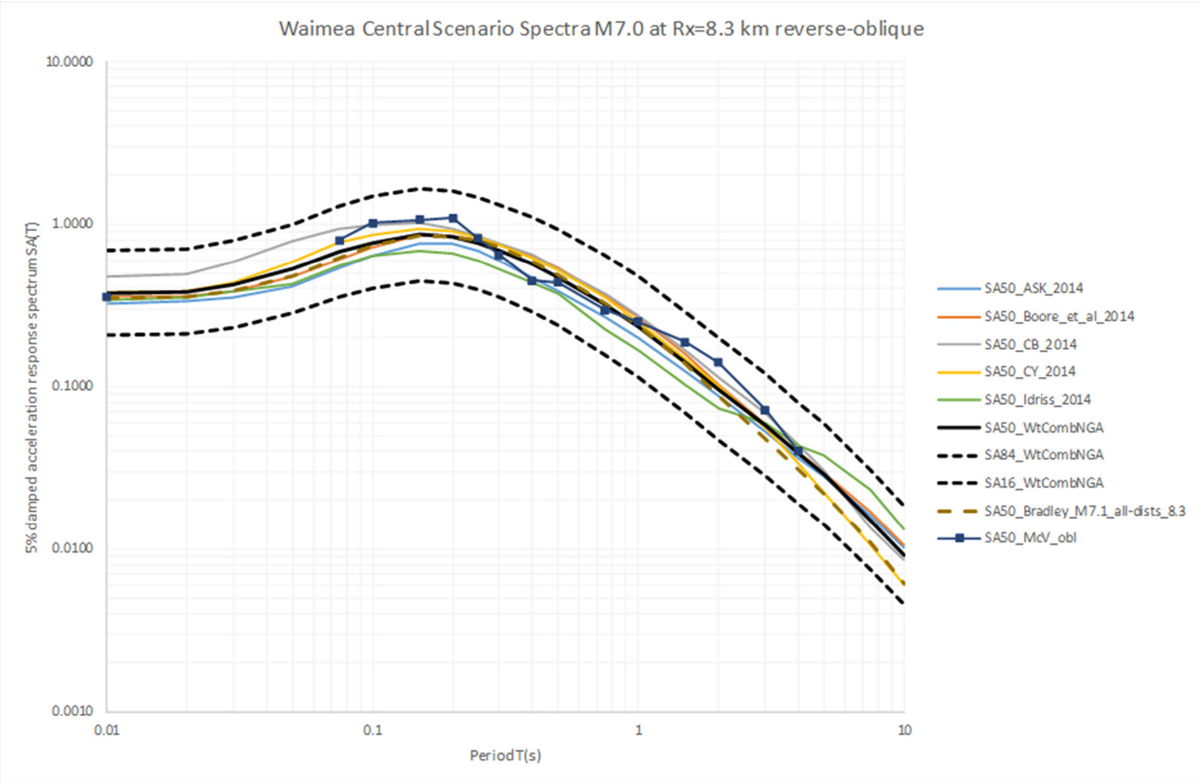

Figure 3.1 Median scenario spectra for rupture of the Waimea Central fault segment. Note the shoulders on the Idriss spectrum (green) at about 2-3s period, and at 4-5s period, and the general similarity of the CY (yellow) and Bradley (dashed brown) spectra.

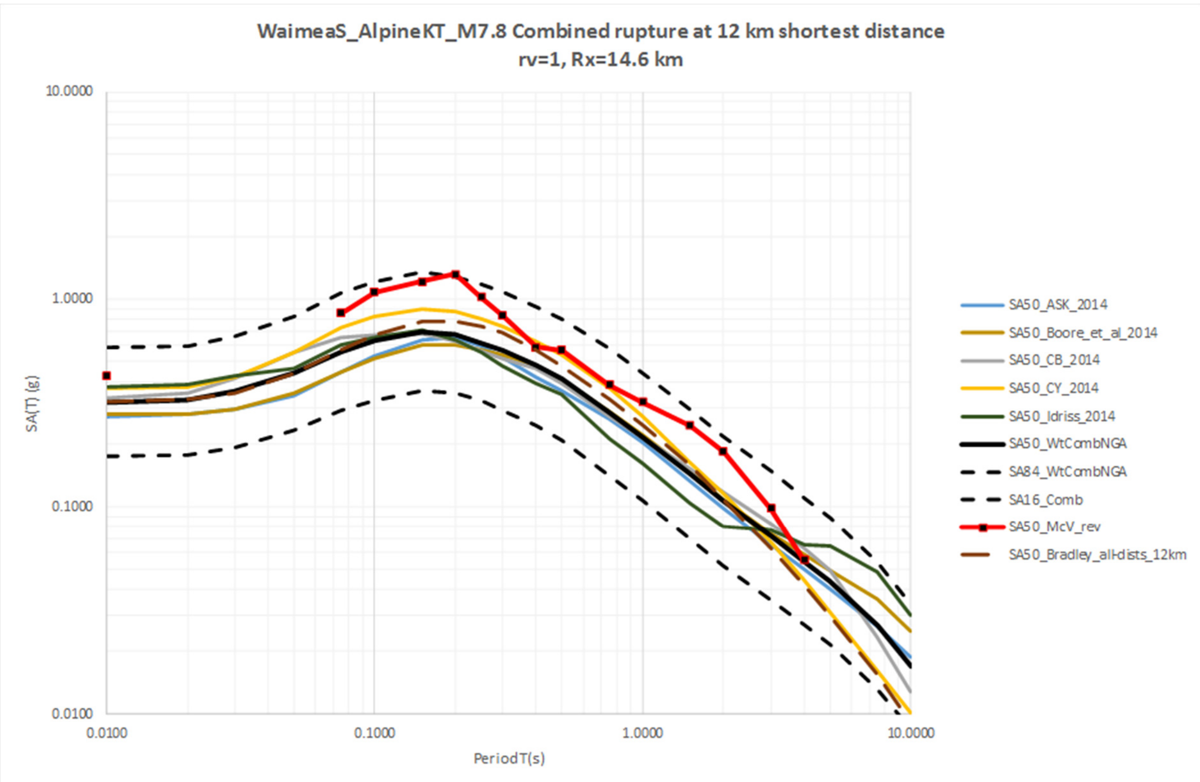

Figure 3.2 Median scenario spectra for rupture of the combined Waimea south and Alpine K-T fault segments. Note the shoulders on the Idriss spectrum beyond about 2s period, and the general similarity of the CY (yellow) and Bradley (dashed brown) spectra.

3.3 SUBDUCTION ZONE MODELS

The selection of subduction zone models is less important for the seismic hazard at the proposed Waimea Dam than selection of the crustal models, given the presence of the nearby surface faults and the relatively large distance between the site and the Hikurangi Subduction Interface dipping under Marlborough from offshore of Cape Campbel. For these hazard calculations, the subduction zone models of Abrahamson et al. (2016), Atkinson and Boore (2003; 2008), McVerry et al. (2006), and Zhao et al. (2006) are selected. These four models were recommended by Van Houtte (2017) for use in New Zealand PSHA. These models are applied with equal weights.

4.0 HAZARD CALCULATIONS

Given the changes in 2015 to the New Zealand Dam Safety Guidelines (NZSOLD, 2015) since the previous report was completed in 2011, a full update of the hazard estimates for Waimea dam has been undertaken. The update includes consideration of epistemic uncertainties in both the ground-motion prediction equations (GMPEs) and fault modelling. Epistemic uncertainties are those resulting from insufficient knowledge or simplification in the models, as opposed to random variability. An important change affecting the determination of the Safety Evaluation Earthquake (SEE) motions for this study is that the 2015 Guidelines require deterministic (or ‘scenario’) spectra to be considered at the 84th-percentile level.

To address the uncertainties in ground-motion predictions required by the 2015 NZSOLD Guidelines, the hazard estimates were performed using a GMPE logic tree in the OpenQuake engine, an open source software developed by Global Earthquake Model (GEM) Foundation as a best-practice engine for hazard and risk calculation and modelling (GEM, 2017). The selection of GMPEs used and their weightings are discussed in Section 3.

The brief calls for peak ground accelerations and 5% damped acceleration response spectra to be developed both with and without magnitude weighting (or scaling). In magnitude-weighting for structural applications, response spectrum values for magnitude M are scaled by the Idriss (1985) factor of (M/7.5)1.285 for periods between 0s and 0.5s, as used in the New Zealand Standard NZS170.5:2004 (Standards New Zealand, 2004), while the unweighted estimates have no scaling of the expected accelerations. This factor is intended to produce estimates that are equivalent to magnitude 7.5 values in terms of damage-potential. Magnitude-weighting addresses the criticism that uniform-hazard spectra tend to be dominated by contributions from moderate-magnitude earthquakes, and do not reflect the effect of duration in causing structural damage. Duration depends strongly on magnitude. The Idriss (1985) factor was originally developed for assessing liquefaction potential. Idriss references a study by Kennedy et al. (1984) for the US Nuclear Regulatory Commission that shows that the magnitude-weighting factors developed for liquefaction studies are also relevant to the response of ductile structures.

For liquefaction analyses, the Idriss (1985) expression has been replaced by more modern relations with stronger dependence on magnitude.

As discussed in Section 3.0, the results are presented for the geometric mean of the horizontal components. Vertical PGAs and spectra are outside the scope of this study.

4.1 OPEN QUAKE SOFTWARE/PSHA SOFTWARE

The hazard calculations for this assessment were calculated using the March 2017 Version 2.3 of the OpenQuake Engine. OpenQuake (OQ) is a suite of open-source software developed by Global Earthquake Model (GEM) Foundation to promote consistent use of data and facilitate best practices in seismic hazard and risk calculation (GEM, 2017).

We utilise an updated version of the 2010 National Seismic Hazard Model (NSHM) (Stirling et al. 2012). The most significant change to the fault modelling from the 2010 NSHM model is the updating of the modelling of the Waimea Fault (see Section 2). This is combined with the use of multiple GMPEs rather than the single GMPE (McVerry et al. 2006) used in the earlier report (Buxton et al., 2011) for the dam site.

The OQ implementation of the GMPE logic tree (Section 3.2) is used to produce hazard curves and response spectra, one for each branch of the logic tree. The hazard curves for each of the logic tree branches are combined according to the associated weights to produce a single hazard curve and response spectrum. Spectra for the 16th, 50th and 84th percentiles along with the mean are reported.

In addition to the comprehensive treatment of epistemic uncertainty represented in the GMPE logic trees, the PSH calculations also consider the aleatory variability in ground motions from the GMPEs. All of the GMPEs have published standard deviations, and the PSH calculations consider the variability in predicted ground motions up to the 3-standard deviation level. This is frequently-used practice in PSHA globally.

The OQ software is also used to produce 50th- and 84th-percentile estimates of spectra for several fault-rupture scenarios, including the combined rupture of several fault segments that are treated as independent sources in the probabilistic estimates. These include the same weighted combinations of crustal GMPEs used for the probabilistic calculations, and use the same fault geometries (apart from linking together some fault segments) to ensure consistent calculations of distances and hanging-wall factors with the probabilistic calculations.

4.2 PROBABILISTIC HAZARD SPECTRA

Tables 4.1 and 4.2 respectively list the probabilistic mean and 84-percentile estimates of the 5% damped acceleration response spectra for return periods of 150 years, 500, 2500 and 10,000 years, for the preferred fault source parameters. The results are given both unweighted (UW) and with magnitude-weighting (MW) up to periods of 0.5s. The weighting for magnitude M is (M/7.5)1.285, as used in developing the spectra of NZS1170.5:2004. The values are for RotD50 (very similar to the geometric mean) versions of the GMPEs. Hanging wall factors have been incorporated in all the GMPEs.

The mean unweighted spectra are plotted in Figures 4.1 and 4.2, on linear and log-log plots. These figures also show the mean spectra for the case where the average recurrence interval of the southern segment of the Waimea Fault has been reduced from 5600 years to 4000 years, in recognition of the possibility that the fault's slip rate increases towards the south as it becomes closer to the higher strain rate Wairau and Alpine faults. The effect of this change on the hazard estimates is slight, a maximum of less than 2% at the peak of the 10,000-year spectrum, and generally much less than that.

Figures 4.3 and 4.4 show the probabilistic 50th- and 84th-percentile unweighted spectra for the preferred fault source model for the combination of all the GMPEs, as well as the mean spectra shown in Figures 4.1 and 4.2. The 50th-percentile spectra are very similar to the mean spectra listed in Table 4.1, and are virtually indistinguishable from them in the plots, except at long spectral periods and return periods.

Figures 4.5 and 4.6 compare the unweighted and magnitude-weighted spectra, on linear and log scales. Magnitude-weighting generally has only minor effects on these spectra, with the largest effects at the peaks of the spectra, which are reduced by about amounts ranging from about 15% for the 150-year spectrum down to about 4% for the 10,000-year spectrum.

Table 4.1 Summary of mean estimates of 5% damped unweighted (UW) and magnitude-weighted (MW) acceleration response spectra for Waimea dam for preferred fault source parameters.

Period T(s)	Mean 5% damped acceleration response spectra SA(T) (g)							
	Return Period							
	150 years		500 years		2500 years		10,000 years	
	UW	MW	UW	MW	UW	MW	UW	MW
0	0.15	0.13	0.25	0.22	0.42	0.40	0.64	0.62
0.075	0.29	0.24	0.47	0.40	0.82	0.75	1.26	1.18
0.1	0.34	0.28	0.55	0.48	0.99	0.90	1.52	1.44
0.15	0.36	0.31	0.59	0.53	1.06	0.99	1.65	1.58
0.2	0.36	0.31	0.59	0.53	1.04	0.99	1.61	1.55
0.25	0.32	0.28	0.52	0.48	0.91	0.88	1.40	1.36
0.3	0.29	0.26	0.47	0.44	0.82	0.80	1.25	1.23
0.35	0.26	0.24	0.42	0.40	0.75	0.74	1.14	1.13
0.4	0.24	0.22	0.38	0.37	0.68	0.67	1.04	1.04
0.5	0.20	0.18	0.33	0.32	0.58	0.59	0.90	0.91
0.75	0.14		0.24		0.43		0.67	
1	0.11		0.19		0.34		0.53	
1.5	0.081		0.13		0.25		0.38	
2	0.058		0.101		0.18		0.28	
3	0.036		0.066		0.12		0.19	

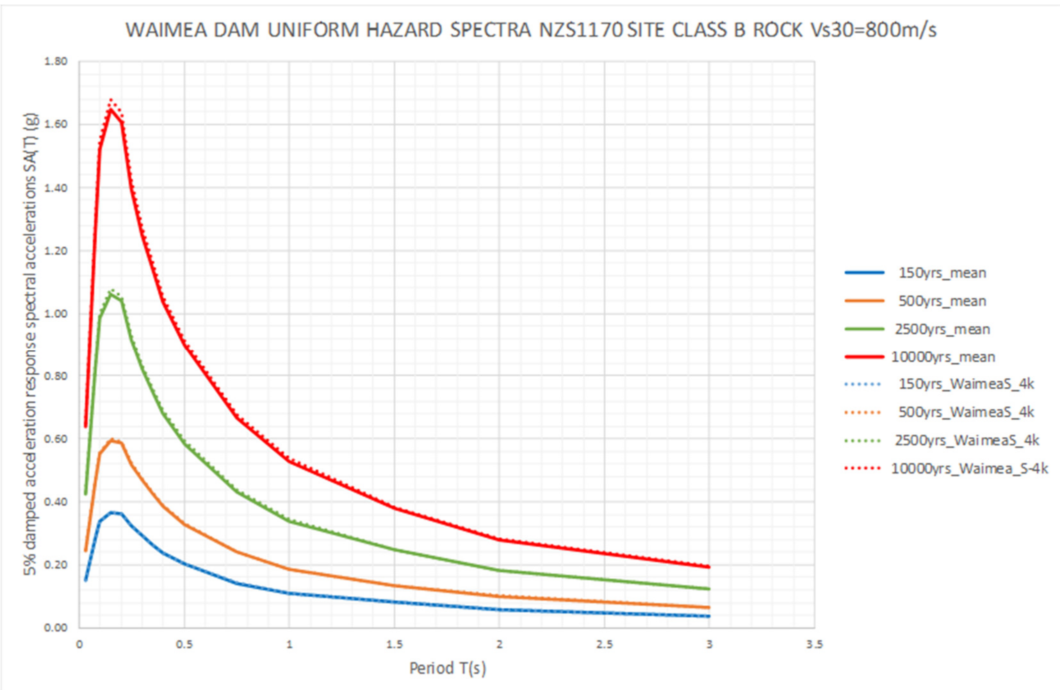

Figure 4.1 Waimea Dam mean 5% damped acceleration response spectra for return periods of 150, 500, 2500 and 10,000 years for preferred fault source model and model with shorter recurrence interval of 4000 years rather than 5600 years for the Waimea South fault source. There is no magnitude-weighting.

Table 4.2 Summary of 84-percentile estimates of 5% damped unweighted (UW) and magnitude-weighted (MW) acceleration response spectra for Waimea dam for preferred fault source parameters.

Period T(s)	84-percentile 5% damped acceleration response spectra SA(T) (g)							
	Return Period							
	150 years		500 years		2500 years		10,000 years	
	UW	MW	UW	MW	UW	MW	UW	MW
0	0.17	0.14	0.27	0.24	0.46	0.45	0.69	0.69
0.075	0.32	0.26	0.52	0.44	0.91	0.82	1.39	1.28
0.1	0.38	0.32	0.62	0.53	1.09	0.99	1.66	1.58
0.15	0.41	0.34	0.65	0.57	1.14	1.09	1.79	1.71
0.2	0.42	0.36	0.66	0.60	1.17	1.11	1.86	1.76
0.25	0.36	0.32	0.56	0.53	0.98	0.94	1.49	1.46
0.3	0.32	0.29	0.51	0.47	0.88	0.85	1.36	1.32
0.35	0.29	0.26	0.46	0.44	0.81	0.78	1.25	1.22
0.4	0.26	0.24	0.42	0.40	0.74	0.72	1.14	1.12
0.5	0.23	0.21	0.36	0.35	0.64	0.64	0.99	1.00
0.75	0.17		0.27		0.48		0.77	
1	0.13		0.21		0.38		0.60	
1.5	0.11		0.17		0.30		0.44	
2	0.083		0.13		0.22		0.33	
3	0.059		0.099		0.17		0.26	

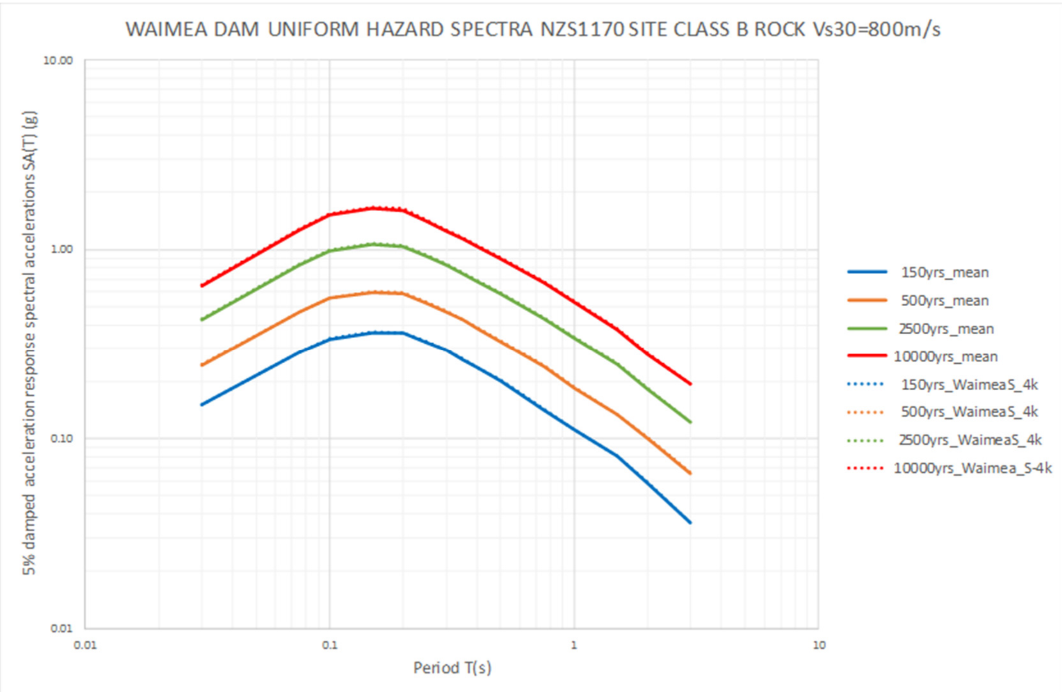

Figure 4.2 Spectra of Figure 4.1 on log-log plot.

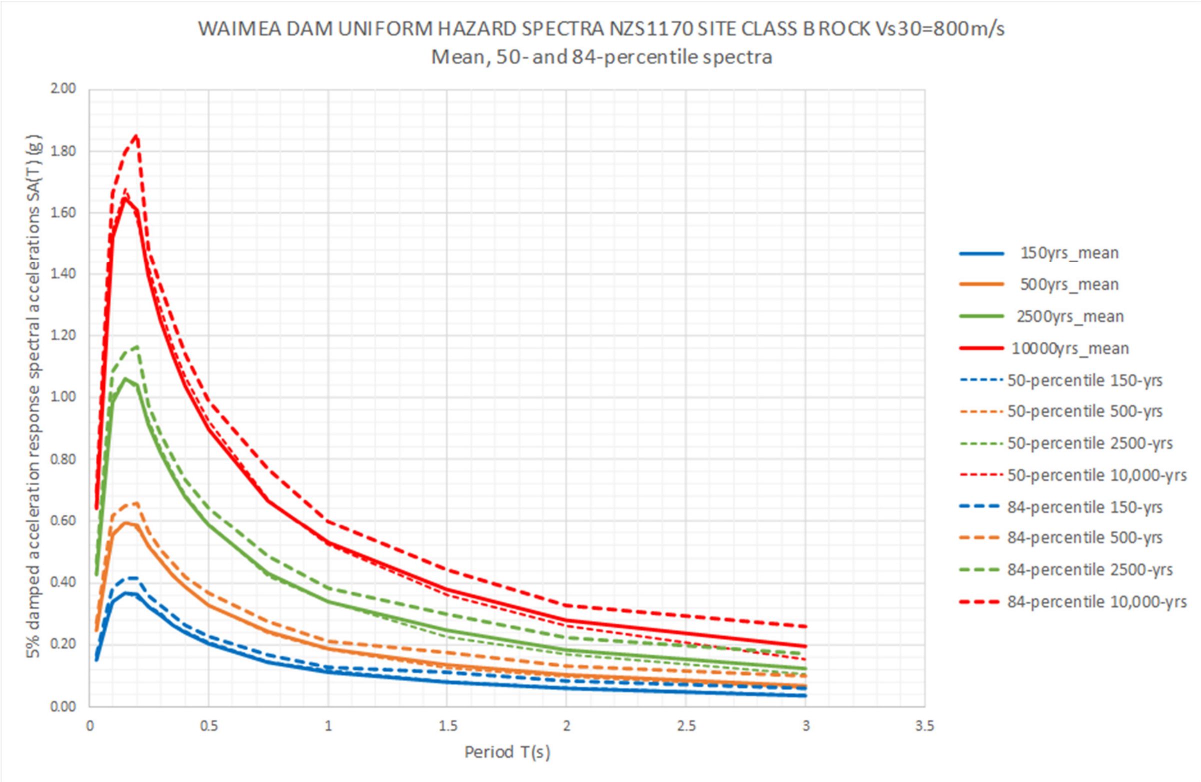

Figure 4.3 Mean spectra from Figure 4.1 for the preferred fault source model with the addition of the 50- and 84-percentile spectra for the weighted combination of all the GMPEs.

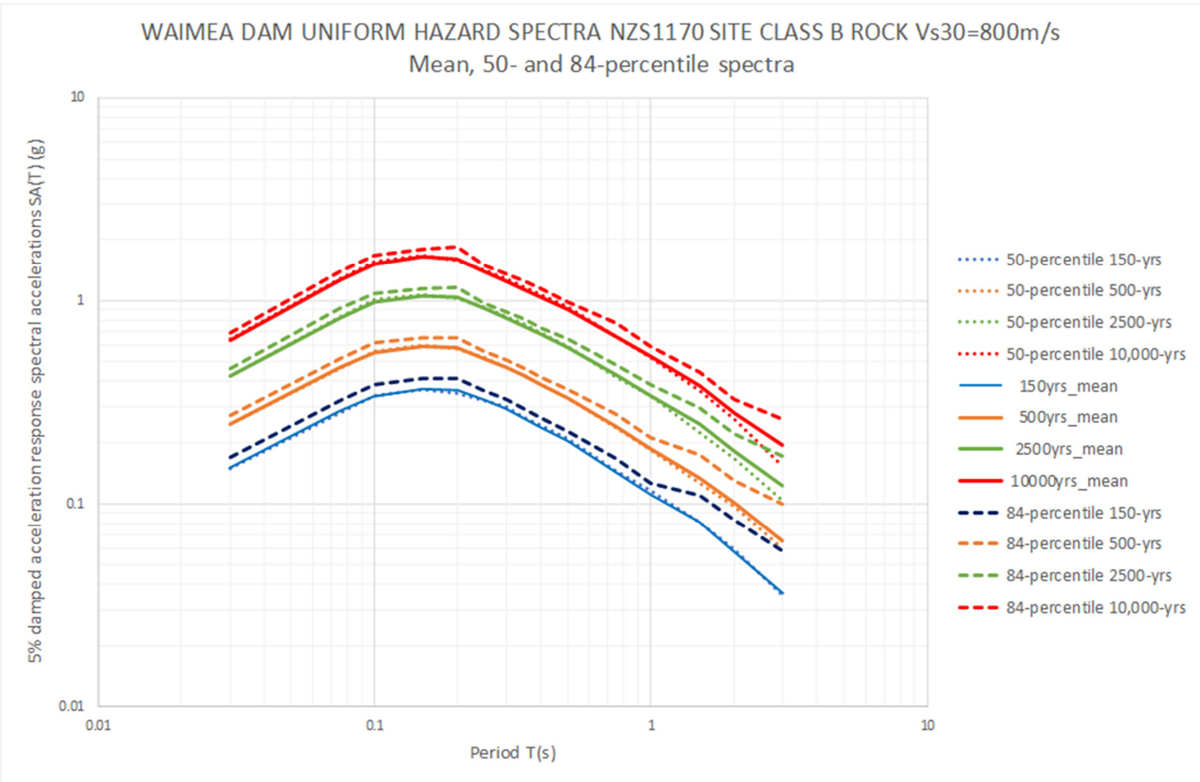

Figure 4.4 Spectra of Figure 4.3 on log-log plot.

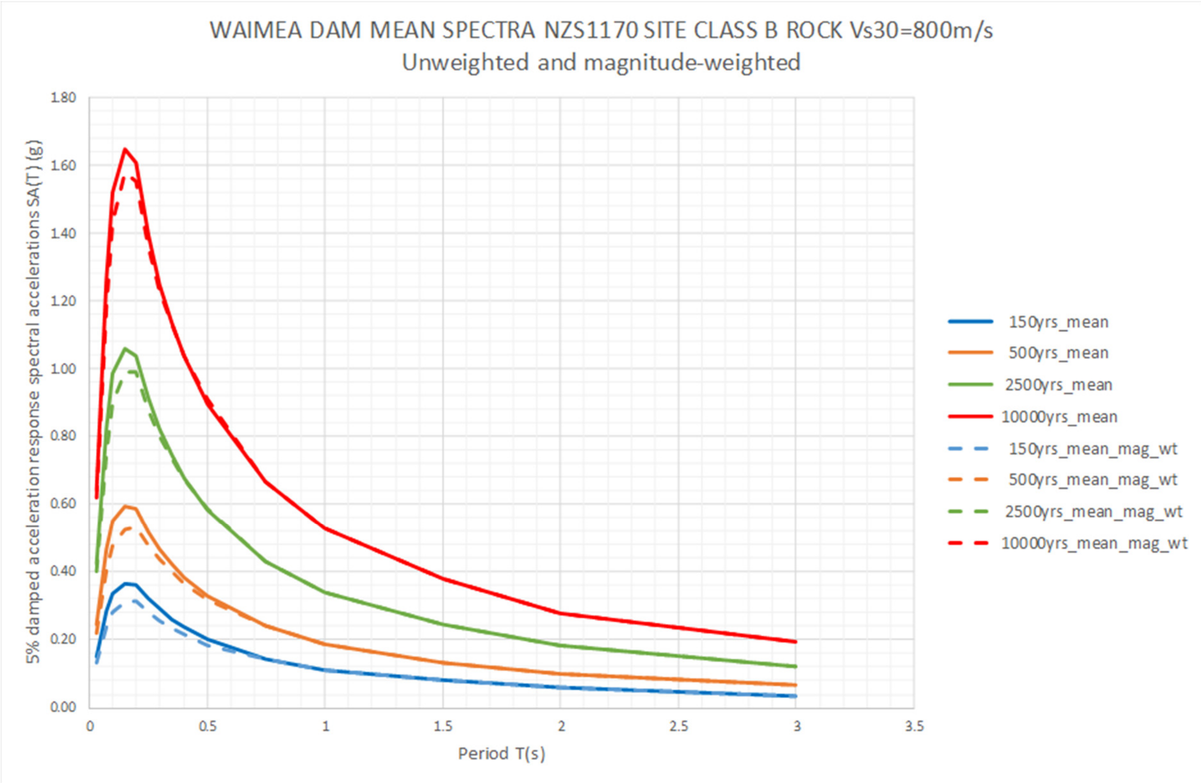

Figure 4.5 Waimea Dam mean spectra and mean magnitude-weighted spectra for return periods of 150, 500, 2500 and 10,000 years for the preferred fault source model.

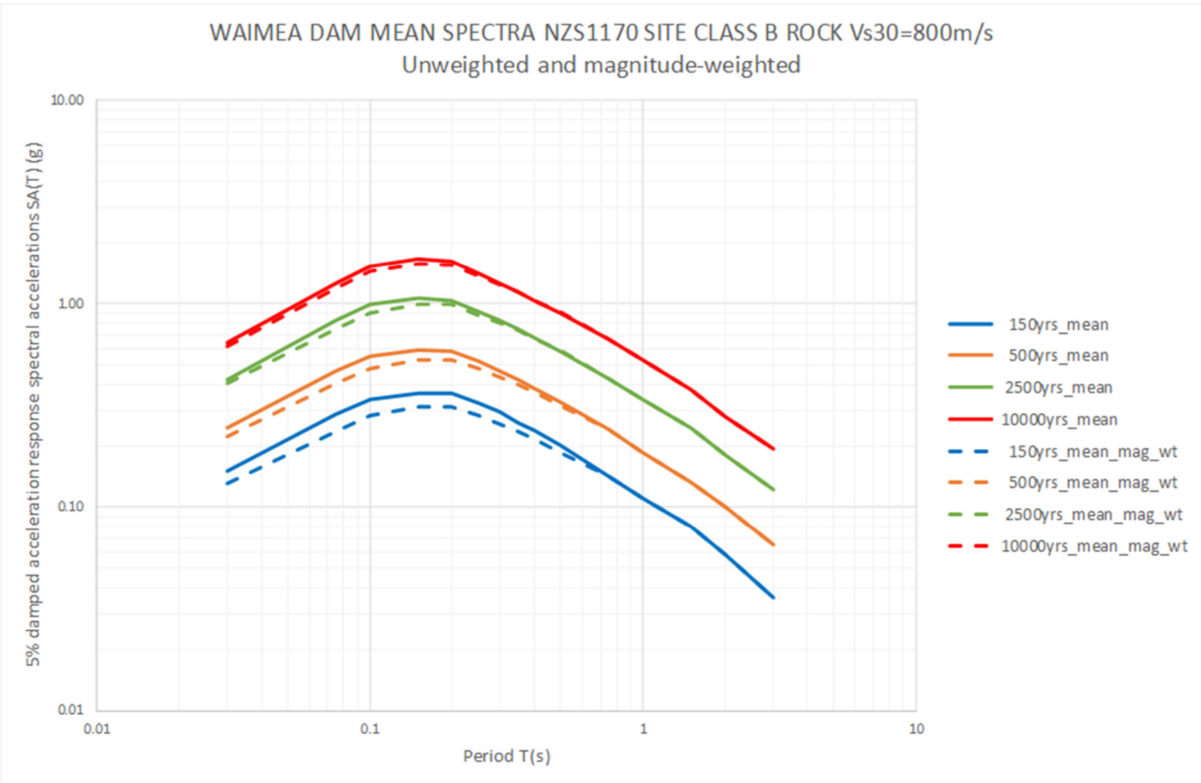

Figure 4.6 Spectra of Figure 4.5 on log-log plot.

4.3 COMPARISON WITH 2011 SPECTRA

The uniform hazard spectra of this study are compared with the spectra from the 2011 study (Buxton et al., 2011) in Figure 4.7. The spectra from the current study (bold curves) involving the combination of all GMPEs are considerably reduced from those of the 2011 study (large dashed curves). It appears that most of the change is caused by differences in the seismicity models, in that the current results using only the McVerry et al. (2006) GMPE (dotted curves) cross over the current results combining all GMPEs. Only the McVerry GMPE was used in the 2011 study.

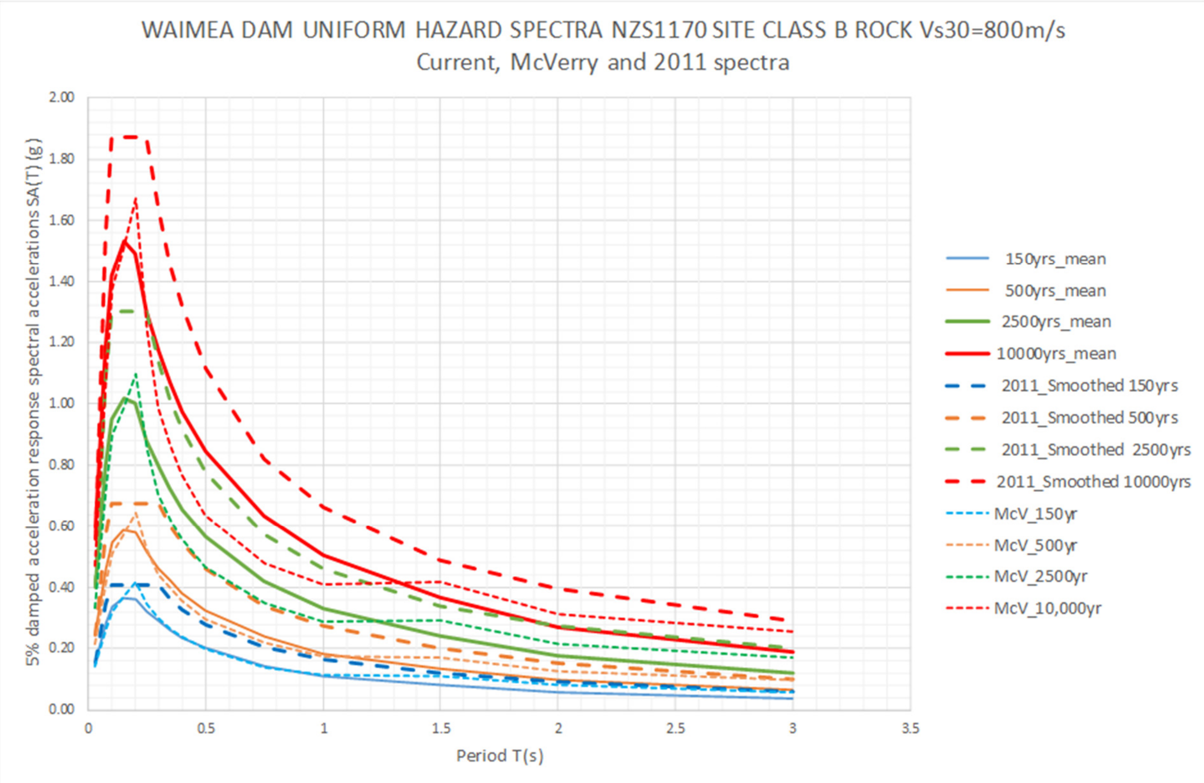

Figure 4.7 Comparison of probabilistic hazard results from this study from the combination of all GMPEs (solid curves) with those of the 2011 study (large dashed curves) and those of the current study using only the McVerry GMPE (dotted curves).

4.4 DETERMINISTIC SCENARIO SPECTRA

For high Potential Impact Classification (PIC) dams, such as the proposed Waimea Dam, the New Zealand Dam Safety Guidelines (NZSOLD, 2015) allow deterministic estimates of scenario motions as alternatives to the mean 10,000-year spectrum. The deterministic motions are required to be the 84th-percentile motions associated with the SEE earthquake at the 84th-percentile level for the Controlling Maximum Earthquake (CME). The SEE is the earthquake that would result in the most severe ground motion which a dam structure must be able to endure without uncontrolled release of the reservoir. The CME is the earthquake capable of inducing the largest seismic demand on a dam.

Spectra for three multi-segment and one single-segment fault-rupture scenarios have been considered as alternatives to the mean 10,000-year spectrum for the Safety Evaluation Earthquake (SEE) motions. The scenarios considered were: combined rupture of the central and southern segments of the Waimea Fault in a magnitude 7.5 earthquake at a shortest distance of about 8 km from the dam site; a single-segment rupture of the central segment of the Waimea Fault in a magnitude 7.1 earthquake at a shortest distance of about 8 km; combined rupture of the Waimea South and Alpine sources in a magnitude 7.8 earthquake at a shortest distance of about 12 km from the dam site; and combined rupture of the Wairau and Alpine Faults in a magnitude 8.3 earthquake at about 21 km shortest distance.

The mean 50th- and 84th-percentile estimates of these scenario spectra are shown in Figures 4.8 and 4.9, in linear and log plots. These spectra are found by taking the 50th- and 84th-percentile estimates (median and one standard deviation above the median) for each GMPE, and then determining the weighted-average for the 5 GMPEs considered. Also shown are the mean uniform hazard spectra for return periods of 150, 500, 2500 and 10,000 years. None of these spectra are magnitude-weighted. The 84th-percentile scenario spectra range from around the mean 2500-year motions to stronger than the mean 10,000-year motions. The 50th-percentile scenario spectra generally lie between the 500- and 2500-year probabilistic spectra.

Determination of the SEE motions involves evaluation of the mean 10,000-year hazard spectrum and the 84th-percentile scenario spectra. The two strongest 84th-percentile scenario spectra, both involving rupture of the central segment of the Waimea Fault, one scenario with rupture in combination with the south segment and the other for rupture on its own, exceed the mean 10,000-year spectrum, so need not be considered for the SEE motions according to the NZSOLD (2015) Guidelines. The mean of the 84th-percentile spectra for the combined Alpine-Waimea South sources is very close to the mean 10,000-year spectrum, although slightly exceeding it in the period range 0.15s to 1s. Thus, the mean 10,000-year spectrum should be taken as the SEE motions, but the 84th-percentile motions for combined rupture of the Alpine-Waimea Sources in a magnitude 7.8 earthquake at a distance of about 12 km can be taken as one approximate realisation of this spectrum.

Table 4.3 Summary of mean estimates of 5% damped unweighted acceleration response spectra for Waimea dam for a return period of 10,000 years and for the 84th-percentile spectra for three multi-segment and one single-segment fault-rupture scenarios. These are the candidates for the SEE motions.

Period T(s)			Mean 5% damped acceleration response spectra SA(T) (g)		
			Return Period or Scenario		
	10,000yrs	Waimea Central and South 84th-percentile	Waimea Central 84th-percentile	Waimea South and Alpine 84th-percentile	Wairau and Alpine 84th-percentile
0	0.64	0.74	0.70	0.60	0.44
0.075	1.26	1.47	1.39	1.15	0.79
0.1	1.52	1.76	1.67	1.36	0.93
0.15	1.65	1.97	1.85	1.54	1.07
0.2	1.61	1.94	1.81	1.54	1.10
0.25	1.40	1.70	1.57	1.36	1.00
0.3	1.25	1.50	1.38	1.22	0.91
0.35	1.14	1.37	1.24	1.11	0.84
0.4	1.04	1.25	1.13	1.03	0.78
0.5	0.90	1.06	0.95	0.88	0.68
0.75	0.67	0.76	0.67	0.64	0.51
1	0.53	0.60	0.51	0.52	0.41
1.5	0.38	0.40	0.33	0.36	0.31
2	0.28	0.28	0.23	0.27	0.23
3	0.19	0.17	0.13	0.18	0.16

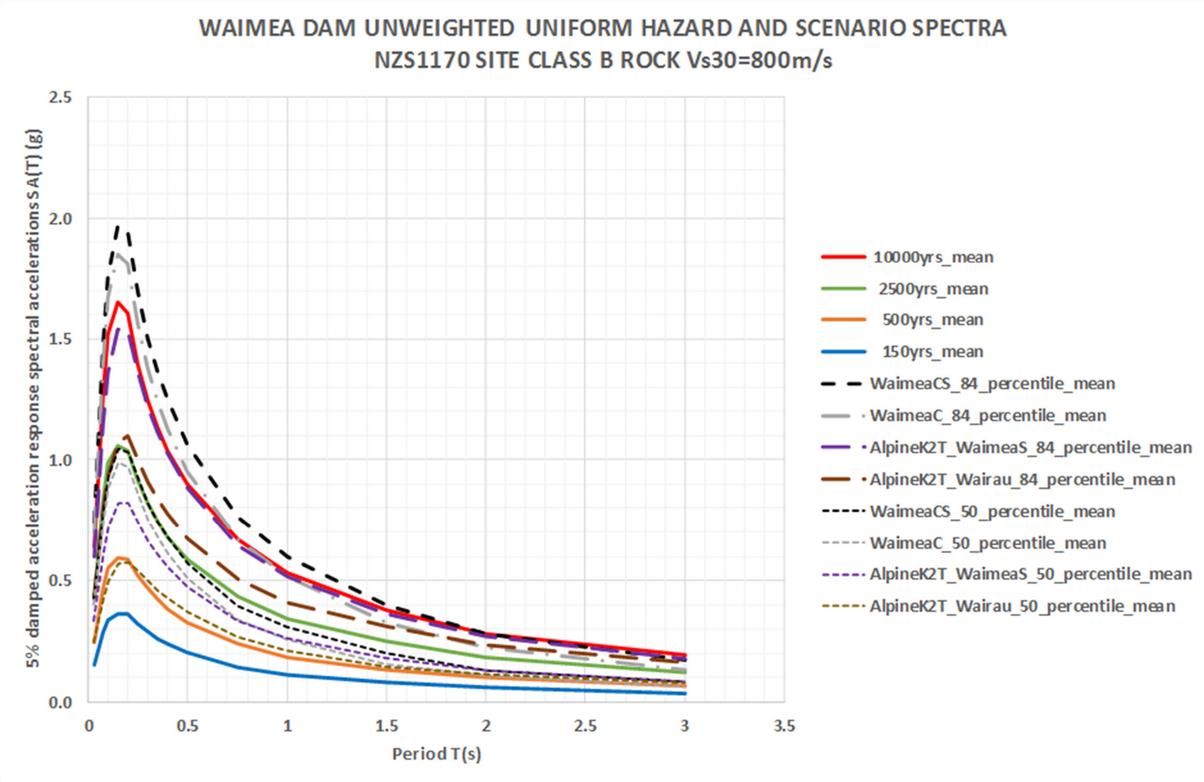

Figure 4.8 Comparison of mean uniform hazard spectra of Figure 4.1 (solid lines) with the mean estimates (over the 5 GMPEs) of the 50th - and 84th -percentile spectra for three multi-segment rupture scenarios. Figure 4.8 The mean 10,000-year spectrum is very similar to the mean estimate of the 84th-percentile motions for the combined Alpine-Waimea South sources. The two strongest 84th-percentile scenario estimates, for the combined rupture of the central and south segments of the Waimea Fault and for rupture of the central segment of the Waimea Fault on its own, exceed the mean 10,000-year spectrum, so need not be considered for the SEE motions according to the NZSOLD (2015) Guidelines.

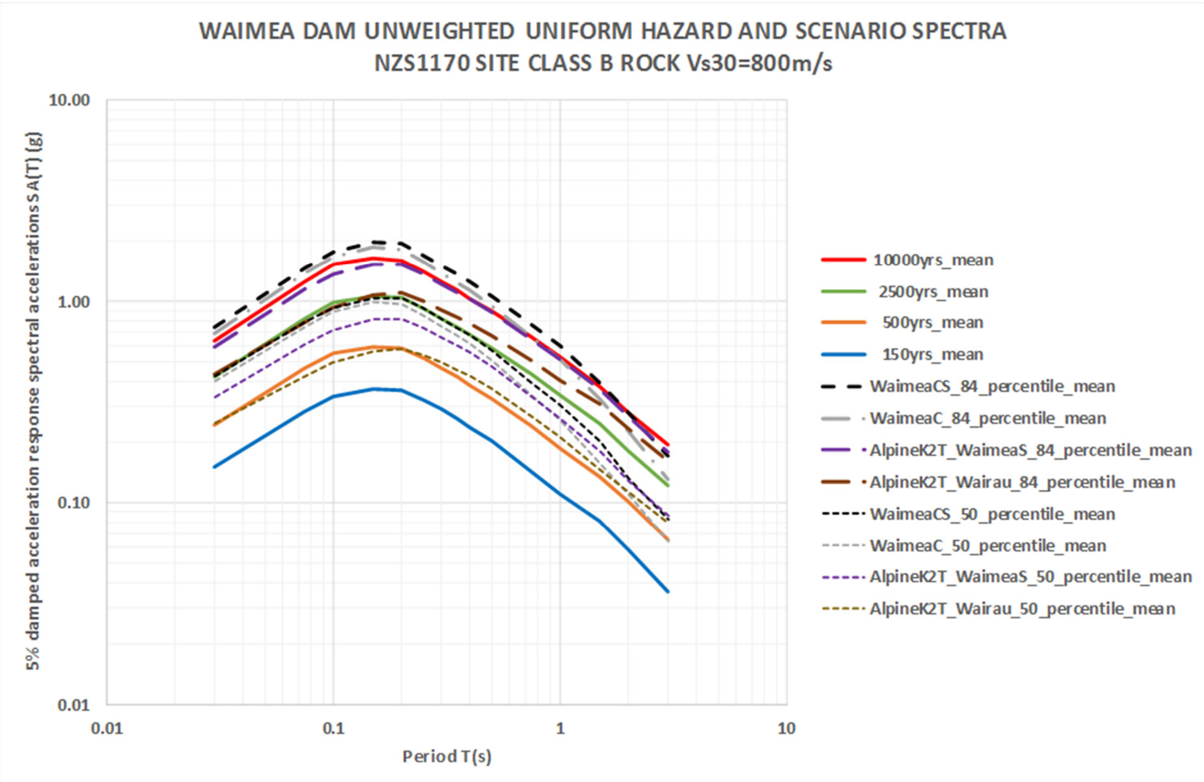

Figure 4.9 Spectra of Figure 4.8 on a log-log plot.

4.5 DEAGGREGATION OF 1 IN 10,000 AEP HAZARD

Deaggregation of the percentage contributions by magnitude and distance to the exceedance rate of the 10,000-year PGA are provided in Figure 4.10, by magnitude cells of 0.2 units width and distance cells of 20 km width. The main contributions totalling nearly 60% come from magnitude 7.1 earthquakes on the central and southern segments on the Waimea Fault, at shortest distances to the proposed dam site of about 8 km and 12 km respectively. These events have average recurrence intervals of 5800 and 5600 years, respectively (Table 2.1).

Table 4.4 lists the percentage contributions by magnitude, together with the percentage cumulative contributions. Only the cell for magnitude 7.0-7.2 and distance 0-20 km, corresponding to the Waimea central and south segments, produces contributions exceeding 10%. The average magnitude for the contributions to this PGA level is 7.2, boosted from the magnitude of 7.1 associated with the Waimea Fault by small contributions at larger magnitudes from the Alpine Fault (magnitude 7.7 at 32 km distance) and Hikurangi interface sources (magnitudes 8.1 to 8.9 at distances of about 100 to 120 km).

The OQ software amalgamates the contributions of the sources by magnitude and distance cells, and does not provide the contributions of individual faults. However, the contribution of the central segment of the Waimea Fault must be larger than that of the south segment, whose contributions are combined in the cell for magnitude range 7.0-7.2 and distance range 0-20 km distance, because it is at a shorter distance of about 8 km compared to about 12 km from the dam site, and these two sources have the same magnitude of 7.1, and similar average recurrence intervals of rupture of 5800 and 5600 years.

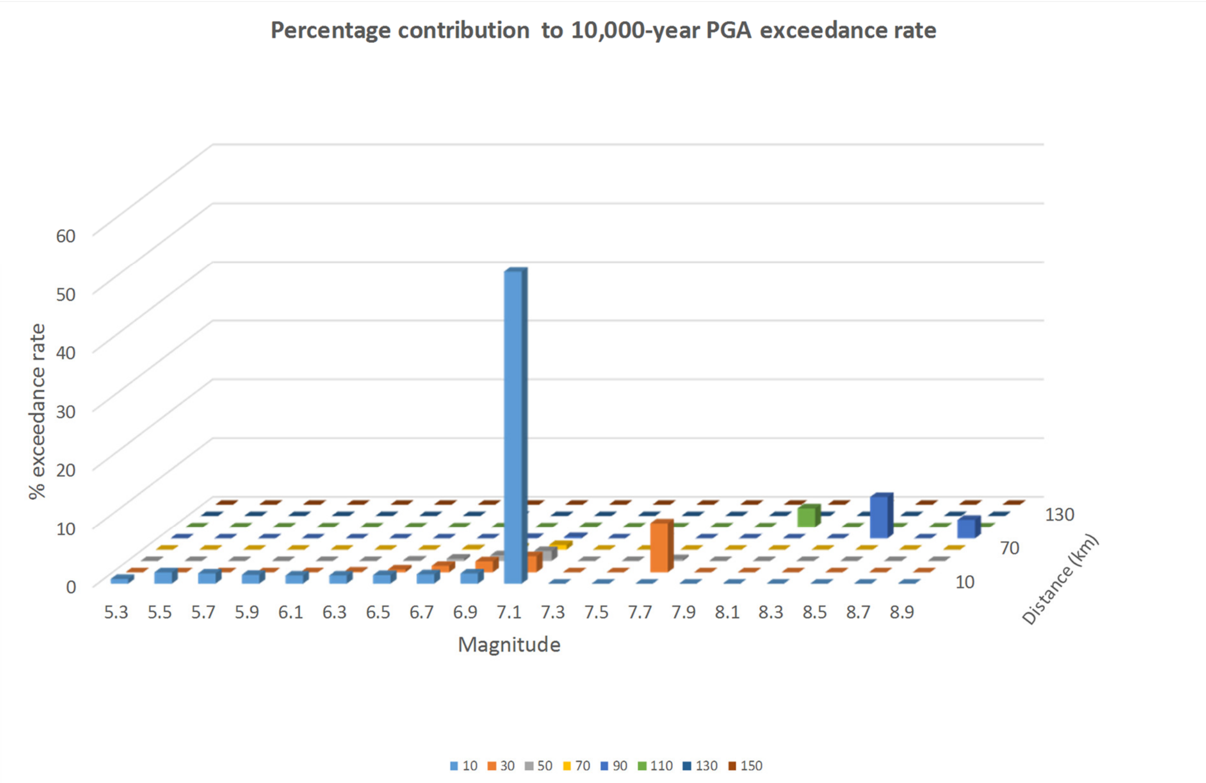

Figure 4.10 Percentage contribution by magnitude and distance to exceedance rate of 1/10,000 AEP PGA. Nearly 60% of the contribution is from the Central and South segments of the Waimea Fault producing magnitude 7.1 earthquakes at shortest distances of about 8 and 12 km, respectively, from the proposed dam site.

Table 4.4 Percentage contribution by magnitude to 1/10,000 AEP PGA.

Magnitude	% Contribution	Cumulative
5.3	0.80	0.80
5.5	1.93	2.73
5.7	1.74	4.47
5.9	1.51	5.98
6.1	1.41	7.39
6.3	1.52	8.91
6.5	2.02	10.93
6.7	3.17	14.10
6.9	4.96	19.06
7.1	58.70	77.76
7.3	0.00	77.76
7.5	0.00	77.76
7.7	8.69	86.44
7.9	0.00	86.44
8.1	3.24	89.69
8.3	0.00	89.69
8.5	7.11	96.79
8.7	0.00	96.79
8.9	3.21	100.00
Average magnitude by contribution = 7.2		

4.6 AFTERSHOCK MOTIONS

The 2015 NZSOLD Guidelines require consideration of shaking in aftershock motions for high PIC dams, because ‘SEE shaking may lead to cracking, increased seepage and reduced strength. … The information will enable the determination of dam stability following an aftershock.’ The requirements are that ‘For the purposes of dam safety assessments at least one aftershock of one magnitude less than the CME should be anticipated within one day of the SEE.’ The Guidelines also discuss multiple aftershocks in days to months after the mainshock, with a need to consider dam stability over the period until repairs can be completed.

The *Guidelines* define the CME as ‘The maximum earthquake on a seismic source that is capable of inducing the largest seismic demand on the dam ‘. However, they do not discuss whether the CME motions exclude those that need not be considered as scenario motions for the SEE motions, because they exceed the mean 10,000-year probabilistic motions. The *Guidelines* also do not state the percentile level that should be considered for the aftershock motions.

There are several candidates for the CME motions for the proposed Waimea Dam, as it is not clear whether these need be taken as stronger than the SEE motions. For Waimea Dam, it was recommended that the SEE motions be taken as the mean probabilistic 10,000-year motions. The largest contribution to the exceedance rate of the 10,000-year motions is from magnitude 7.1 earthquakes on the central segment of the Waimea Fault, at a shortest distance of about 8 km from the dam site. The 10,000-year spectrum was very similar to the 84th-percentile spectrum for a scenario earthquake involving combined rupture of the Waimea South and Alpine Kaniere-Tophouse fault segments, in a magnitude 7.8 earthquake at a shortest distance of 12 km. Two stronger scenario spectra were not required to be considered in determining scenario candidates for the SEE motions, because they exceed the 10,000-year probabilistic spectrum. The excluded scenarios are for rupture of the central segment of the Waimea Fault (the largest contributor to the probabilistically-determined SEE spectrum), and for combined rupture of the Waimea Central and South segments, in a magnitude 7.5 earthquake at 8 km distance. Although not required to be considered for the SEE spectrum, it is not clear whether stronger of these (for the combined rupture of the two segments) need to be considered as contributing the CME motions.

This leads to three candidates for aftershock motions:

i. A magnitude 6.1 earthquake on the central segment of the Waimea fault at a distance of about 8km (aftershock of largest contributor to the probabilistically-determined SEE motions, and a disallowed deterministic contender for the SEE motions);

ii. A magnitude 6.5 earthquake on the central segment of the Waimea Fault at a shortest distance of 8 km (aftershock of the disallowed Waimea Central-South deterministic contender for the SEE motions);

iii. A magnitude 6.8 earthquake on the south segment of the Waimea Fault at a distance of about 12 km (aftershock of the combined rupture of the Waimea South and Alpine Kaniere-Tophouse fault segments).

Spectra for these three aftershock scenarios are plotted in Figure 4.11, at the 50th- and 84th-percentile levels, and compared to the uniform hazard spectra for the dam site. The 84th-percentile spectra for the two aftershocks involving the Waimea Central fault segment lie closer to the 10,000-year than to the 2500-year spectrum at short periods. The two associated main shock spectra exceed the 10,000-year spectrum, so were not required to be considered as SEE spectra. The 84th-percentile spectrum for a magnitude 6.8 aftershock of the combined rupture of Alpine Kaniere-Tophouse and Waimea South fault segments lies close to the 2500-year spectrum, exceeding it at short spectral periods and falling below it for periods of about 0.75s and longer. This spectrum appears to be at a level more appropriate for consideration as an aftershock spectrum, given that it is significantly reduced from the SEE spectrum. This is consistent with the associated main shock spectrum lying very close to the 10,000-year SEE spectrum.

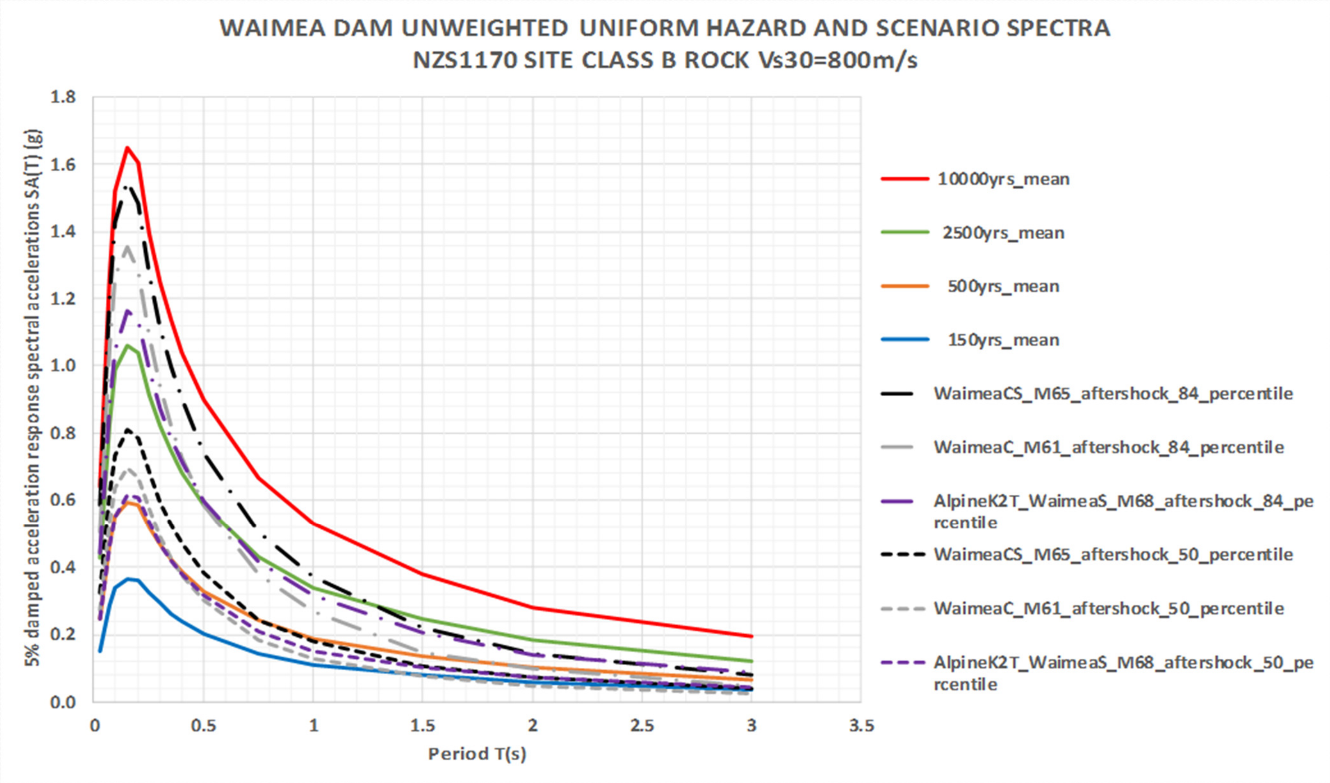

Figure 4.11 Spectra for three candidate aftershock events, plotted at the 84th-percentile (dash-dot curves) and 50th-percentile (small dashes) and compared with the uniform hazard curves (solid curves). The three events are a magnitude 6.5 aftershock following combined rupture of the Waimea Central and South fault segments (WaimeaCS, black curves), a magnitude 6.1 aftershock of rupture of the Waimea Central fault segment on its own (WaimeaC, grey curves), and a magnitude 6.8 aftershock of the combined rupture of the Alpine Kaniere-Tophouse and Waimea South fault segments (Alpine K2T_WaimeaS, purple curves).

Table 4.5 Three candidate aftershock scenario spectra.Selection of the M6.8 Waimea South and Alpine event as the aftershock is consistent with the associate aftershock spectrum being similar to the10,00-year SEE spectrum.

Period T(s)	84th-percentile aftershock spectra (g)		
	M6.1 Waimea Central aftershock	**M6.5 Waimea Central-South aftershock**	**M6.8 Waimea South and Alpine aftershock**
0	0.50	0.58	0.44
0.075	1.05	1.20	0.88
0.1	1.27	1.43	1.05
0.15	1.36	1.55	1.16
0.2	1.28	1.49	1.13
0.25	1.09	1.27	0.99
0.3	0.94	1.11	0.87
0.35	0.82	1.00	0.78
0.4	0.73	0.90	0.71
0.5	0.58	0.74	0.60
0.75	0.38	0.50	0.42
1	0.27	0.37	0.32
1.5	0.15	0.22	0.21
2	0.099	0.14	0.14
3	0.049	0.082	0.087

5.0 CONCLUSIONS AND RECOMMENDATIONS

Acceleration response spectra for 5% damping have been estimated for Waimea Dam, updating the earlier study of Buxton et al. (2011) by incorporating an updated seismicity model, including modelling of the Waimea Fault as three rather than two source segments, and by using the weighted combination of five ground-motion prediction equations (GMPEs) rather than the one used in 2011.

- Spectra have been estimated for NZS1170.5 Site Class B Rock site conditions, with an assumed average shear-wave velocity Vs30 over the top 30 metres of 800m/s.
- The five GMPEs used are McVerry et al. (2006); Bradley (2013); Abrahamson, Silva & Kamai (ASK, 2014); Boore, Stewart, Seyhan and Atkinson (BSSA, 2014); and Campbell & Bozorgnia (CB, 2014), with weights of ASK 1/6; BSSA 1/6; CB 1/6; Bradley 3/10 and McVerry 2/10.
- Probabilistic mean and 84th-percentile spectra have been estimated for return periods of 150, 500, 2500 and 10,000 years, with and without magnitude-weighting. The values are for RotD50 (very similar to the geometric mean) versions of the GMPEs. Hanging wall factors have been incorporated in all the GMPEs.
- Magnitude-weighting generally has minor effects on the probabilistic hazard spectra for this study.
- The 50-percentile spectra are very similar to the mean spectra, except at long spectral periods and return periods.
- The effect on the hazard estimates of reducing the average recurrence interval of the southern segment of the Waimea Fault from 5600 years to 4000 years is slight, a maximum of less than 2% at the peak of the 10,000-year spectrum.
- Deterministic spectra for various rupture scenarios have also been produced, including considering multi-fault ruptures (combined Waimea Central and South fault segments, combined Waimea South and Alpine Kaniere-Tophouse source, and combined Wairau and Alpine Kaniere-Tophouse source).
- The strongest 84th-percentile scenario estimates, for the combined rupture of the central and south segments of the Waimea Fault, exceed the mean 10,000-year spectrum, so need not be considered for the SEE motions according to the NZSOLD (2015) Guidelines.
- The Safety Evaluation Earthquake (SEE) motions have been recommended as the probabilistically determined mean 10,000-year spectrum.
- The mean estimate of the 84th-percentile motions for the combined Alpine-Waimea South sources is very similar to the 10,000-year probabilistically-based SEE spectrum.
- The probabilistic spectra estimated in the current study are considerably reduced from those of the 2011 study, with the change appearing to result mainly from the seismicity model rather than the use of a combinations of GMPEs in place of the single one used in 2011.
- The main contribution (about 60% of the total) to the exceedance rate of the 10,000-year spectrum is from the central and south segments of the Waimea Fault, modelled as producing magnitude 7.1 earthquakes at distances of 8 km and 12 km, respectively, from the dam site.

- The contribution-averaged magnitude for the 10,000-year peak ground accelerations is 7.2, because of the contributions of larger magnitude sources in addition to those of the Waimea Fault.
- The recommended aftershock spectrum corresponds to the 84_{th}-percentile spectrum for a magnitude 6.8 earthquake at 12 km distance from the dam site, following a magnitude 7.8 main-shock corresponding to a combined rupture of the Alpine Kaniere-Tophouse and Waimea South fault segments.

6.0 ACKNOWLEDGEMENTS

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