Overview of Site Effects and the Application of the 2022 New Zealand NSHM in the Wellington Basin, New Zealand

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ABSTRACT

We provide an overview of the treatment of site effects in the New Zealand National Seismic Hazard Model (NZ NSHM), including a case study of basin effects in central Wellington. The NZ NSHM 2022 includes a change in site parameter from subsoil class (NZS class) to V_{S30}. Poor NZ V_{S30} characterization is a major source of uncertainty in the NSHM; however, advanced site characterization in Wellington allows for in-depth study. First, we construct a regional 3D shear-wave velocity model and maps of site parameters (T_0, NZS class, and V_{S30}) for central Wellington. At central city soil sites, we find the ratios of NZ NSHM 2022 hazard spectra with respect to the current equivalent design spectra range from factors of ~0.8–2.6 (median ~1.5), depending on local site conditions and spectral period. Strong amplification peaks at 0.5–2 s are observed in central Wellington. Linear site-specific amplifications from multiple methods are compared at 13 stations and are well-defined by both site-to-site residuals and response spectral ratios relative to station POTS. At many deeper soft sites (V_{S30} < 300 m/s), strong amplification peaks occur around T_0 that are underpredicted by mean ergodic ground-motion model (GMM) predictions. This underprediction is slightly enhanced when using basin-specific $Z_{1.0}$ as an additional site parameter. Our study highlights outstanding challenges in modeling strong basin response within shallow basins in NSHMs, including the need to consider region- or basin-specific modeling approaches as well as nonlinear effects at high shaking intensities that dominate the hazard. For New Zealand, in general, as illustrated in the Wellington case study, a priority is the further characterization of V_{S30} (and V_S) for the seismic network to better isolate and quantify uncertainties in seismic hazard and allow useful exploration of regional–GMM adjustments and partially nonergodic approaches.

KEY POINTS

- New maps of site parameters V_{S30}, T_0, and site class are constructed for central Wellington.
- The change in primary site parameter to V_{S30} significantly influences hazard calculations across Wellington.
- A subset of Wellington stations show strongly peaked basin amplification around the fundamental site period.

INTRODUCTION

Quantifying local site response and its uncertainty presents one of the most promising avenues to quantify and reduce uncertainties in seismic hazard calculations. The New Zealand National Seismic Hazard Model (NZ NSHM) revision program has included a site working group to further these long-term goals. Here, we summarize key findings from this group, drawing on a series of detailed technical studies summarized in Table 1.

It is well known that local geological conditions, including the presence of softer sedimentary layers, basin structures, and topographic features, strongly influence local site response. In

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TABLE 1
Topics and Bibliographic References for Publications of the New Zealand National Seismic Hazard Model (NZ NSHM) 2022 Site Working Group

Topic Number	Topic	Bibliographic References
1	2022 NSHM revision for New Zealand: an overview of the treatment of site/basin effects: a case study of the Wellington basin	Kaiser *et al.* (2022)
2	NSHM: Site Characterization Database summary report	Wotherspoon *et al.* (2022, 2024)
3	Three-dimensional geological modeling of Wellington Quaternary sediments and basin geometry	Hill *et al.* (2022)
4	Three-dimensional ground-motion simulation-based site amplification considering multiple basin geometries: a Wellington, New Zealand, case study	Lee *et al.* (2022) and R. Lee *et al.* (unpublished report, 2024; see Data and Resources)
5	Combining observed linear basin amplification factors with 1D nonlinear site-response analyses to predict site response for strong ground motions: application to Wellington, New Zealand	de la Torre *et al.* (2022, 2023)
6	High spatial resolution amplification map for Wellington city using hybrid standard spectral ratio	Manea *et al.* (2024)
7	Evaluation of Wellington basin site amplifications based on ground-motion modeling	Atkinson (2023a)
8	Analysis of site-response residuals from empirical ground-motion models to account for observed sedimentary basin effects in Wellington, New Zealand	C. A. de la Torre *et al.* (unpublished report, 2024; see Data and Resources)

basins, complex seismic wavefields can be generated, arising from 3D effects including focusing and scattering, waveguides, and the generation of surface waves within the basin or at the basin edge. The treatment of these variable local effects in NSHMs poses an ongoing global challenge.

Ground-motion models (GMMs) used in traditional seismic hazard analysis use site proxy parameters to provide robust statistical averages for a given site condition, invoking the ergodic assumption. The ergodic assumption essentially holds that all sites with the same proxy value will have the same response, with some variability. For practical application of NSHMs, a single primary site parameter is commonly used to approximate these effects, most typically V_{S30}, the time-averaged shear-wave velocity (V_S) within the uppermost 30 m of the subsurface profile. This results in a “smoothed” mean prediction across spectral periods, whereas site-specific amplification may exhibit strong frequency-dependent amplification peaks that deviate systematically and significantly from the ergodic mean. Any single parameter alone is limited in its ability to capture these effects, particularly at sites with strong impedance contrasts (generating strong amplification peaks) and complex 3D subsurface structures. Moreover, the choice of primary site parameters (and the associated suite of GMMs) significantly influences hazard calculations at a given site.

The NZ NSHM 2022 revision (Gerstenberger *et al.*, 2024) provides comprehensive new probabilistic hazard calculations, which yield a general increase in calculated seismic hazard for most New Zealand locations. In high seismic hazard areas, such as the capital city of Wellington, hazard changes are largely driven by an updated ground-motion characterization model (GMCM; Bradley *et al.*, 2024) that includes recently developed shallow crustal and subduction GMMs (Bora *et al.*, 2024). However, the change in the primary site parameter from subsoil class (NZS class) to V_{S30} in the NZ NSHM 2022 also significantly impacts local hazard calculations. The NZS class is not primarily defined based on V_{S30}, as summarized in Table 2 (full definition is given in New Zealand’s loading standard NZS1170.5; Standards New Zealand, 2004). Hence, the complex mapping between these two site parameters has implications for local calculated hazard that need to be more fully understood.

Wellington, New Zealand’s capital city, lies above the Wellington sedimentary basin (Fig. 1) and presents a useful first case study to analyze the treatment of site effects in the NZ NSHM 2022. Wellington has experienced well-documented basin amplification effects at 1–2 s in the recent earthquakes (Holden *et al.*, 2013; Kaiser, Balfour, *et al.*, 2017; Bradley *et al.*, 2018). As seen in the 2016 M_w 7.8 Kaikōura earthquake, this basin response has the potential to lead to high spectral accelerations that exacerbate damage to midrise structures (5–15 storeys). Improving the way that these effects are captured in seismic hazard analysis (in Wellington and other New Zealand basins) is a key long-term goal of the NZ NSHM research program.

Here, we analyze the changes in Wellington local hazard calculations with the NZ NSHM 2022. We also summarize progress made by the NSHM site/basin working group on Wellington site characterization and advanced modeling techniques, drawing on a set of underpinning technical reports (Table 1).

We first present the construction of detailed site parameter maps for central Wellington (T_0, NZS class, and V_{S30}) based on an updated 3D geological model and extensive field measurements. We then use these maps to estimate local changes in calculated hazard across the central city based on the 2022 NSHM update. Finally, we present a summary and comparison of site-specific amplification models derived from residual analyses, spectral ratios, and physics-based methods at Wellington strong-motion stations (de la Torre *et al.*, 2022, 2023; Lee *et al.*, 2022; C. A. de la Torre *et al.*, unpublished report, 2024, see Data and Resources; Atkinson, 2023a; Manea *et al.*, 2024). These results provide an evidence base to assess and guide the treatment of site effects in NZ NSHMs.

TABLE 2
NZS1170.5 Subsoil Class (NZS Class) Definitions (Standards New Zealand, 2004)

NZS Class	Description	Definition
A	Strong rock	(a) Unconfined compressive strength (UCS) > 50 MPa & (b) V_{S30} > 1500 m/s & (c) Not underlain by <18 MPa or V_S 600 m/s materials
B	Rock	(a) 1 < UCS < 50 MPa & (b) V_{S30} > 360 m/s & (c) Not underlain by <0.8 MPa or V_S < 300 m/s materials & (d) **A surface layer no more than 3 m depth of highly weathered or completely weathered rock or soil (i.e., material with a UCS < 1 MPa)**
C	Shallow soil	(a) **Not class A, B, or E &** (b) **T_0 < 0.6OR** (c) Depths of soils not exceeding specifications in table 3.2 of NZS1170.5 (Standards New Zealand, 2004).
D	Deep or soft soil	(a) **Not class A, B, or E** (b) **T_0 > 0.6OR** (c) Depths of soil exceeding specifications in table 3.2 of NZS1170.5 (Standards New Zealand, 2004). (d) Underlain by <10 m soils of undrained shear strength < 12.5 kPa or SPT-N < 6
E	Very soft soils	(a) >10 m soils with undrained shear strength <12.5 kPa OR (b) >10 m soils with SPT-N < 6 OR (c) >10 m soils with V_S < 150 m/s OR (d) >10 m combined depth of aforementioned properties.

The table provides a summary of the detailed NZS class definitions of Standards New Zealand (2004). To map NZS class in this study (e.g., Fig. 4), we use the clauses highlighted in bold text to spatially delineate NZS class boundaries. For example, the boundary between NZS classes C and D is estimated from the T0-0.6s contour in this study; however, NZS1170.5 also allows these classes to be determined based on specified maximum depths of soils. SPT-N, standard penetration test values.

TREATMENT OF SITE EFFECTS IN NZ NSHM

Update of the site parameter in the NZ NSHM 2022

The NZ NSHM 2022 (Gerstenberger *et al.*, 2024) marks a significant change in the treatment of site amplification effects in New Zealand. The previous versions of NZ NSHMs (Stirling *et al.*, 2002; Stirling, McVerry, *et al.*, 2012) were based on the single GMM of McVerry *et al.* (2006). This model uses the parameter NZS class defined as discrete classes A (strong rock) through F (very soft soil). These classes are also the basis for the current standard for structural design provisions in New Zealand (NZS1170.5; Standards New Zealand, 2004). The specific definitions of NZS class are complex and summarized in Table 2. Important is the use of a fundamental site period ($T_0 = 0.6$ s) to distinguish between the most common soil sites in New Zealand (NZS classes C and D). In providing this classification, McVerry *et al.* (2006) emphasized that the site amplification from deep deposits of stiff or dense soil is typically greater at long periods than that from shallow sites of the same material (even though the sites may have the same V_{S30}). However, although deeper soil sites could be distinguished using this model, the use of NZS class prevents a nuanced consideration of the influence of shallow soil properties.

The NZ NSHM 2022 is based on more recently developed GMMs, including Next Generation Attenuation (NGA)-West2 (Bozorgnia *et al.*, 2014), NGA-Subduction (Bozorgnia *et al.*, 2022), and NZ backbone models (Atkinson, 2022; Stafford, 2022). A summary of the GMCM is found in Bradley *et al.* (2024). All of the adopted GMMs use the continuous parameter V_{S30} as the primary site parameter for the computation of hazard results. The majority of these models (e.g., Bradley, 2013; Abrahamson *et al.*, 2014; Chiou and Youngs, 2014) also allow for the specification of basin depth parameters such as $Z_{1.0}$ (depth to the 1 km/s shear-wave velocity horizon) or $Z_{2.5}$ (depth to the 2.5 km/s shear-wave velocity horizon). These parameters can be used to further adjust ergodic GMM predictions to capture the average properties associated with basins of given depths. In NZ NSHM 2022, $Z_{1.0}$ and $Z_{2.5}$ are set to the default California-based V_{S30}–$Z_{1.0}$ correlation (Chiou and Youngs, 2014) and V_{S30}–$Z_{2.5}$ correlation (Campbell and Bozorgnia, 2014). The global versions of NGA-Subduction GMMs do not include basin depth parameters. Hence, the default correlations were used only with crustal GMMs, with the exception of the A22 NZ backbone model (Atkinson, 2022), which is based solely on V_{S30}.

The mapping between NZS class and V_{S30} is complex, making direct comparisons of hazards from past NSHMs and the current 2022 revision challenging. Any NZS site class can map to a large possible range of V_{S30} values, and the ranges for each NZS class overlap (see Wotherspoon *et al.*, 2024). Conversely, sites with the same V_{S30} may have different NZS classes; for example, NZS classes C and D sites are distinguished from each other solely by the soil profile beyond 30 m depth. This complex mapping means that to fully evaluate how calculated hazard may change with the NZ NSHM 2022 across an urban area, both the parameters must be well known.

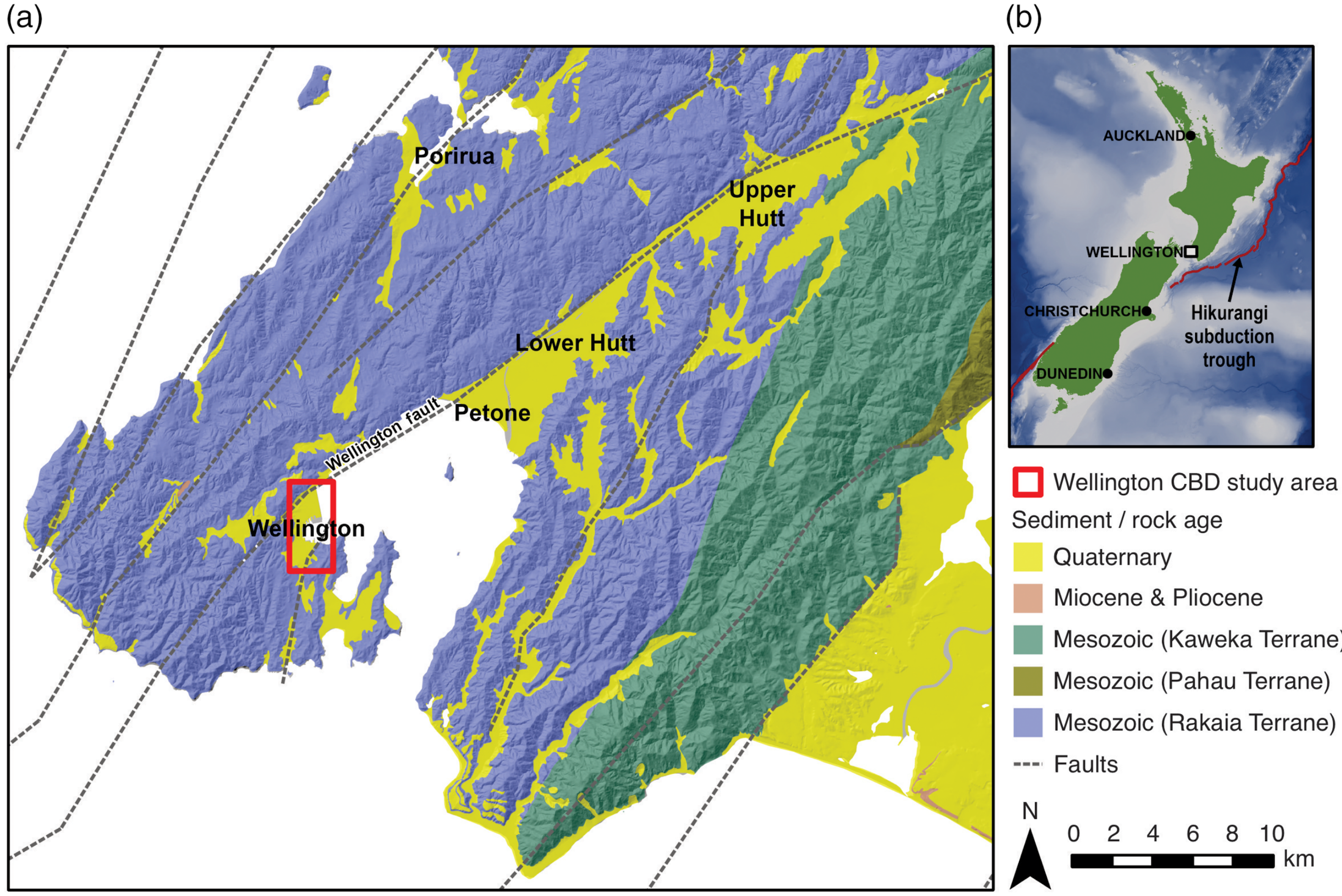

Figure 1. Location of the Wellington basin, extending from Wellington to Petone, Lower Hutt, and Upper Hutt. (a) The extent of the regional-scale geological model of Hill *et al.* (2022); the red rectangle is the Wellington central business district (CBD)—the focus of this study. The simplified geology of the Wellington region is illustrated, including the extent of Mesozoic terranes (basement), Miocene and Pliocene sediments, and the recent Quaternary deposits. Lithological data are sourced from Heron (2020), and faults are from the New Zealand Community Fault Model (Seebeck *et al.*, 2023). (b) Location of the Wellington region in the New Zealand tectonic setting. The color version of this figure is available only in the electronic edition.

New Zealand site characterization

The characterization of V_{S30} and other commonly used site parameters $Z_{1.0}$ and $Z_{2.5}$ is currently limited in New Zealand. This is largely due to the fact that New Zealand's seismic code has been based around the NZS class. T_0 is comparatively better classified (Kaiser *et al.*, 2022; Wotherspoon *et al.*, 2024).

Wotherspoon *et al.* (2022, 2024) present a compilation of site parameters for the New Zealand GeoNet seismic network. Although site characterization has improved with several recent regional studies, and T_0 is generally well characterized across the network, high-quality V_{S30} measurements remain limited to stations within a handful of urban centers (see also Kaiser *et al.*, 2022). For the vast majority of stations, V_{S30} is estimated from the two published New Zealand national-scale V_{S30} models (Perrin *et al.*, 2015; Foster *et al.*, 2019). These models provide only a coarse approximation of V_{S30}, with significant associated uncertainty. Furthermore, the difference between these two models is notable (Fig. 2), and arises due to the different modeling methodologies and assumptions in the absence of measured data. Prior to the NZ NSHM program, the only region where basin-scale mapping of V_{S30} was underpinned by sizeable measured V_S datasets was the Canterbury region (within Foster *et al.*, 2019).

Similarly, only a handful of basins in New Zealand have been characterized to the level at which detailed basin amplification studies can be undertaken (Thomson *et al.*, 2020; Wotherspoon *et al.*, 2020). One such region is the Wellington basin.

WELLINGTON BASIN CHARACTERIZATION

The Wellington basin extends for over 20 km along the Wellington fault, and encompasses the Wellington harbor and Lower Hutt (Figs. 1 and 3). The Wellington central business district is located at the southwestern edge of the basin and comprises the two smaller subbasins of Thorndon and Te Aro (Fig. 3). The underlying subsurface bedrock topography includes strong lateral variations and steeply dipping basin edges (Kaiser *et al.*, 2019; Hill *et al.*, 2022), making the city prone to complex, spatially variable amplification effects.

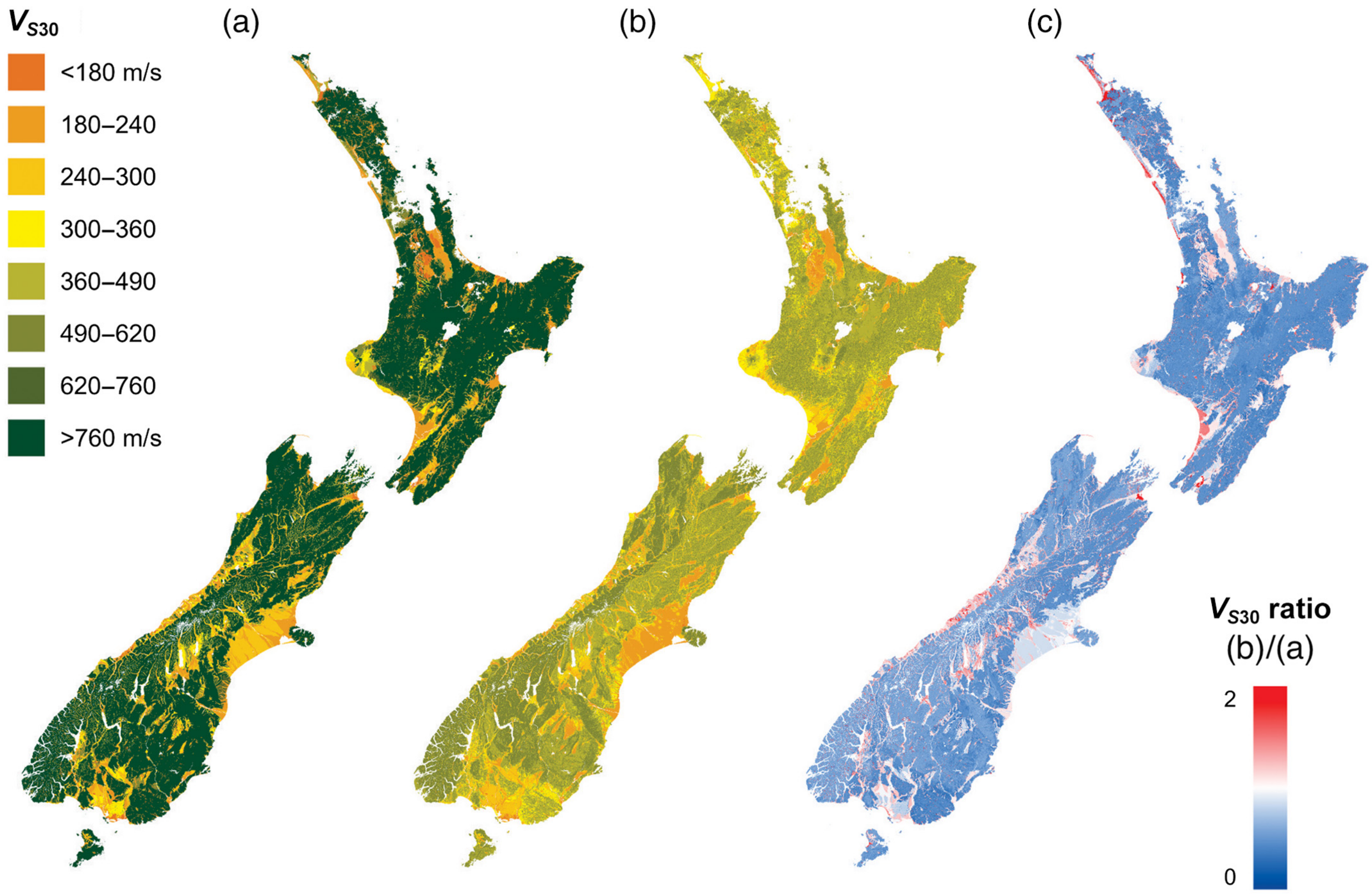

Figure 2. Comparison of national-scale New Zealand V_{S30} models. (a) Perrin *et al.* (2015), based primarily on mapped surface geological units. (b) Foster *et al.* (2019), based on geostatistical analysis. (c) The models show significant differences arising from the modeling methodologies, as illustrated by the ratio of panels (b)/(a). The color version of this figure is available only in the electronic edition.

Furthermore, it is located in a region of high seismic hazard (Gerstenberger *et al.*, 2024). Several faults located within ~50 km of the city are capable of generating M_w 7.5+ earthquakes, including two earthquake sources that dominate the seismic hazard: the Wellington fault and the underlying Hikurangi subduction interface at around ~25 km depth beneath the city (Gerstenberger *et al.*, 2024).

Three-dimensional geological and velocity model

A key advance in the NZ NSHM 2022 program (detailed in Hill *et al.*, 2022) is the synthesis of existing smaller subbasin 3D models in a new continuous 3D geological and velocity model for the wider Wellington basin region (Figs. 1 and 3). The new 3D model is based on much more extensive underpinning geological, geotechnical, and geophysical data, which allow an interpretation of the accumulation of loose to dense Quaternary sediments deposited on weathered Rakaia terrane greywacke basement across multiple subbasin structures. Important is the interface between Quaternary sediments overlying Mesozoic-age greywacke basement at relatively shallow depths (up to ~450 m below the central city; Fig. 3). This interface is associated with a significant impedance contrast that is inferred to be the main contributor to the observed basin-amplification effects in central Wellington. The results of recent gravity surveys (Stronach and Stern, 2021) have also been integrated into the central Wellington section of the model. We observe that large uncertainty associated with basin depth remains in the CentrePort area due to the lack of deep borehole constraints (see discussion in Hill *et al.*, 2022; Manea *et al.*, 2024).

Velocity characterization for each lithological layer in the 3D model follows that of the previous studies and is extended by Hill *et al.* (2022) to encompass 19 lithological subunits defined within the more detailed Wellington city portion of the model. This velocity model is a useful tool to aid in mapping continuous site parameters (next section) as well as providing the basis for numerical modeling of site effects.

Maps of geotechnical parameters (T_0, NZS class, V_{S30}, and $Z_{1.0}$)

New maps of site parameters are constructed based on the 3D velocity model and extensive geophysical, geotechnical and geological datasets. These provide a substantial update to the original mapping of Semmens *et al.* (2010) using the 3D velocity model and much more extensive geophysical, geotechnical, and geological datasets.

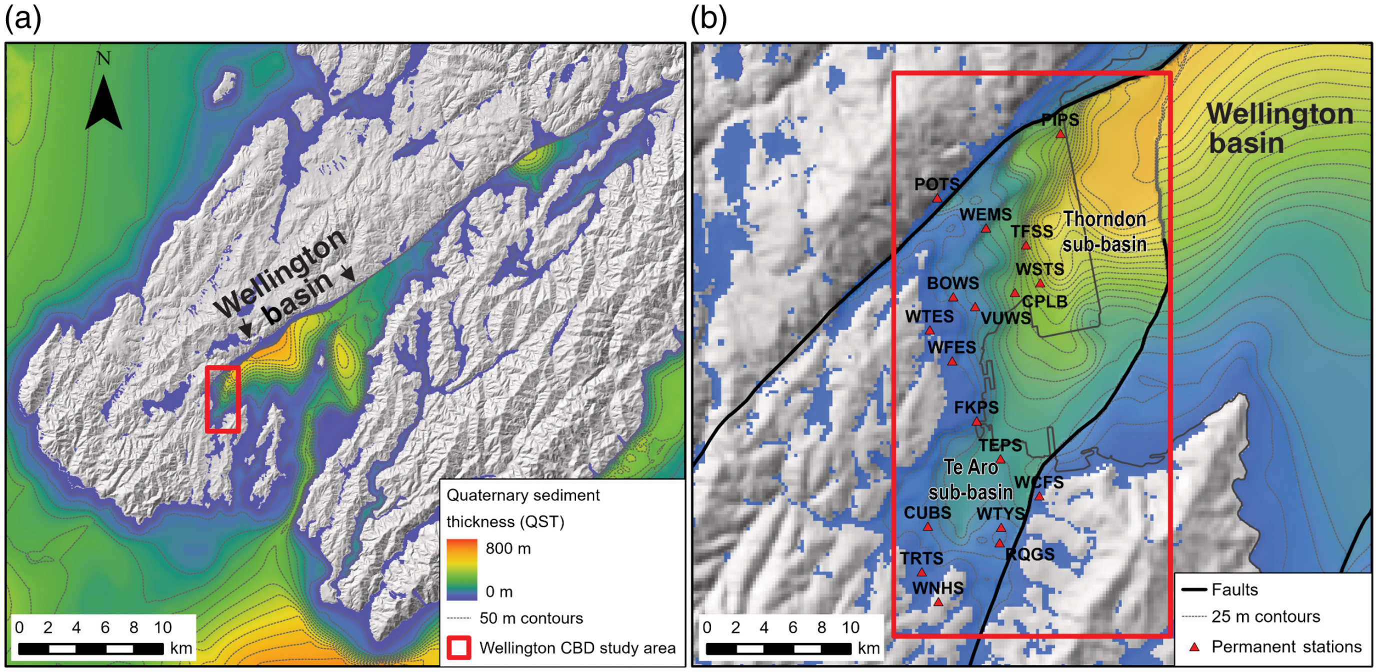

Figure 3. Modeled thickness of Quaternary sediments (QST) from the 3D geological model of Hill *et al.* (2022). QST is generally equivalent to the depth of the greywacke basement within the Wellington basin and is shown for (a) the wider Wellington basin and (b) the central Wellington study area outlined in red. The color version of this figure is available only in the electronic edition.

***T_0*.** A new T_0 map (Fig. 4a; summarized in Kaiser *et al.*, 2019) is based on an extensive curated set of ~380 geophysical horizontal-to-vertical spectral ratio (HVSR) measurements (Vantassel *et al.*, 2018; Kaiser *et al.*, 2019; Manea *et al.*, 2024). To create a continuous map in areas where robust direct measurements are sparse, an approach to optimally combine measured values with estimates based on the 3D model was developed (Kaiser *et al.*, 2019). This provides useful interpolation and extrapolation in shallower areas of the basin and at the basin edges in which HVSR measurements were often difficult to interpret or varied strongly laterally.

T_0 is the longest in the CentrePort area (Fig. 4a), which is the deepest onshore part of the central city subbasins. In the Thorndon subbasin, T_0 shows local variability, which we interpret as arising from strong lateral variations in near-surface material and/or complex site effects associated with the steep-sided basin edge. Within the Te Aro basin, T_0 was very well constrained, with geophysical estimates and those estimated from the 3D model at borehole-to-basement locations showing an excellent match (Fig. 4a; discussion in Hill *et al.*, 2023).

NZS class. An NZS class map is then constructed (Fig. 4b) with the NZS class C and D boundaries derived from the $T_0 = 0.6$ s contour and its uncertainty (e.g., Kaiser *et al.*, 2019). The boundary between NZS classes B and C is derived from the 3 m depth-to-greywacke basement contour extracted from the 3D geological model. An area of softer class D sites where class E cannot be ruled out is outlined by the extent of hydraulic fill and observations of historical liquefaction during the Kaikoura and Cook Strait earthquakes (Cubrinovski *et al.*, 2018).

***V_{S30}*.** A summary map of V_{S30} for central Wellington is also developed in the NZ NSHM 2022 (Kaiser *et al.*, 2022), as shown in Figure 5. The V_{S30} map is underpinned by two components: (1) a database of 50+ measured site-specific V_{S30} values; and (2) a background V_{S30} model based on the 3D geological model and velocity characterization of Hill *et al.* (2023) in the uppermost 30 m.

Measured V_{S30} values are derived from (1) a limited set of downhole V_S profiles and (2) multi-channel analysis of surface wave and other microtremor array studies conducted by the University of Auckland and GNS Science (e.g., Barker *et al.*, 2016; Vantassel *et al.*, 2018). Each V_{S30} estimate has been assigned a quality value according to the scheme of Kaiser, Van Houtte, *et al.* (2017; updated in Wotherspoon *et al.*, 2024), and only the higher-quality (Q1 and Q2) measurements have been included in the final map.

The background estimates of V_{S30} are based on the 3D basin model time-averaged shear-wave velocity of model layers in the uppermost 30 m directly below the site. For some units, the V_S is not well constrained or exhibits considerable variability. Hence, to extract a first assessment of uncertainty in modeled V_{S30}, Monte Carlo simulations are performed (Hill *et al.*, 2023), exploring the range of possible V_S profiles within the given V_S ranges for each unit. From these simulations, the

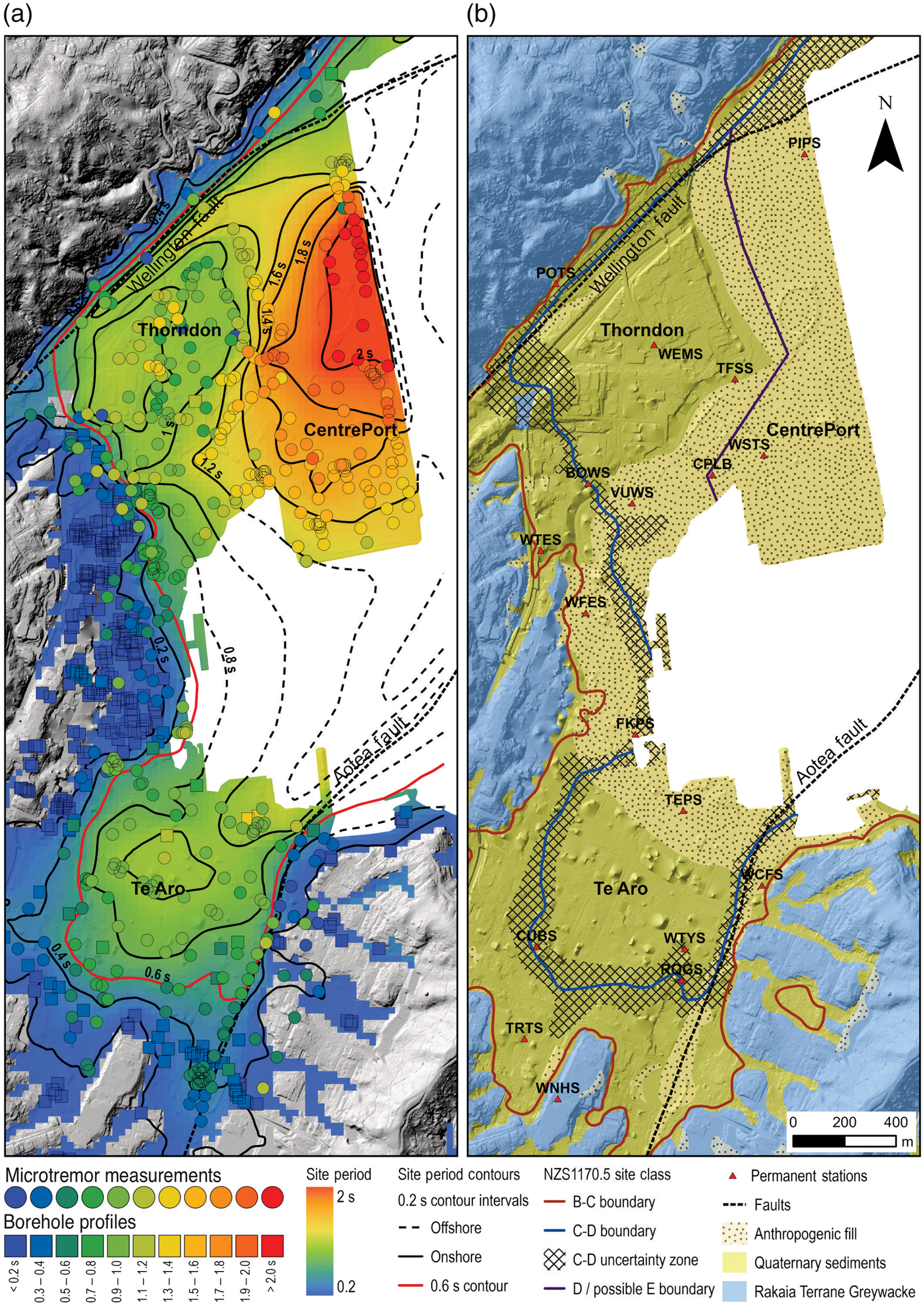

Figure 4. Maps of (a) fundamental site period T_0 and (b) NZS class in central Wellington. (a) T_0 measurements from microtremor HVSR are shown as circles; T_0 estimated from 1D geological borehole profiles down to the basement are shown as squares. (b) NZS class boundaries are shown as thick colored lines overlain on mapped surface geological units. The color version of this figure is available only in the electronic edition.

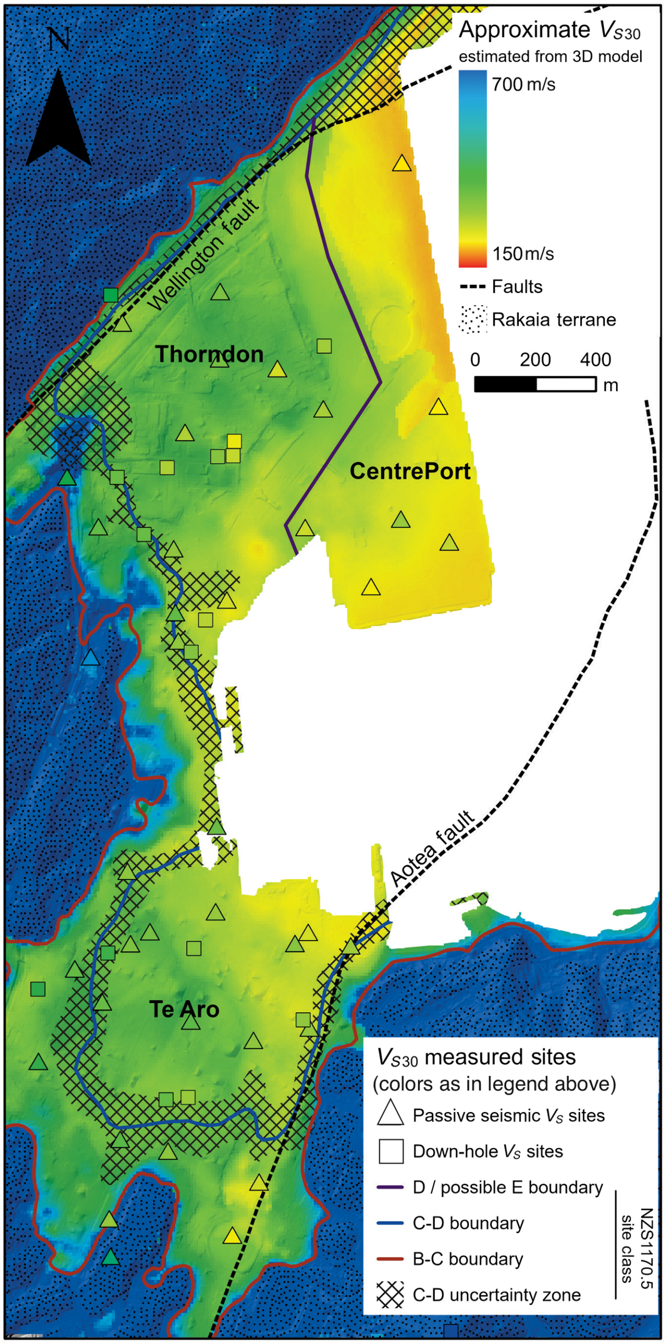

Figure 5. V_{S30} in central Wellington. Background color indicates V_{S30} estimated from the Wellington 3D model detailed in Hill *et al.* (2022, 2023). The symbols indicate the locations of site-specific V_{S30} measurements from downhole investigations (squares) and passive seismic investigations (triangles). The color version of this figure is available only in the electronic edition.

model is estimated to have an average standard deviation of roughly 15% at a given site.

For Wellington, as for New Zealand generally (Wotherspoon *et al.*, 2022, 2024), the V_{S30} at rock sites is not well known. Following Wotherspoon *et al.* (2024), we adopt a generic value of 1000 m/s for moderately weathered greywacke based on the earlier expert elicitation of Kaiser, Van Houtte, *et al.* (2017). However, we acknowledge that greywacke can be highly weathered at the surface in the region, and at such sites or where thin soil layers are present, the generic value is likely to be an overestimate, and the commonly used condition of 760 m/s for soft rock may be more appropriate.

As illustrated in the map, the 3D model provides reasonable approximations of the measured V_{S30}. Some variation is seen in the upper Thorndon area, where model predictions are somewhat higher than the measured values. Central Wellington's near-surface geology shows complexity arising from interbedded alluvial, colluvial, and marginal marine deposits found in the basin. This complexity, including the presence of alluvial channels, can lead to spatial variation in V_{S30} over short spatial scales, which is not fully captured in the model. The V_{S30} map provides a useful guide to V_{S30} conditions, with site-specific study needed to confirm and further constrain the model predictions.

$\boldsymbol{Z_{1.0}}$**.** In Wellington, the large step in velocity at the interface between Quaternary sediments and basement depth is considered a reasonable representation of $Z_{1.0}$ (depth to 1000 m/s material). Thus, the basement depth map in Figure 3 is considered a reasonable proxy for $Z_{1.0}$. This is supported by the limited set of downhole and geophysical measurements to basement that show basin sediments represented by $V_S < 800$ m/s. However, in the deepest onshore part of the basin below CentrePort, $Z_{1.0}$ remains uncertain, with the absence of boreholes to confirm the deeper velocity structure.

NZ NSHM 2022 IN CENTRAL WELLINGTON

NZS class to V_{S30} mapping

The mapping of NZS class to V_{S30} for central Wellington soil sites is shown in Figure 6. This figure illustrates that a given NZS class could be expected to have a large range of associated V_{S30} values, even on a local basin scale such as central Wellington.

This is particularly evident for NZS class C, with values ranging from 200 to >760 m/s (based on the 3D model). This NZS class includes high V_{S30} sites at the basin edges, in which a thin layer of soil overlies the basement, as well as low V_{S30} sites with substantial thicknesses of soft or loose near-surface sediments (e.g., adjacent to the mapped Aotea fault area in Fig. 5).

NZS class D sites show values ranging from 200 to 400 m/s in the measured dataset. The six measurements of V_{S30} in the CentrePort area, where anthropogenic fill is present, lie in the range 200–300 m/s.

2022 Hazard values in central Wellington with respect to current loading standard NZS1170.5

An overview of changes in calculated probabilistic hazard in the NZ NSHM 2022 revision is given for New Zealand's main centers in Bora *et al.* (2024) and Gerstenberger *et al.* (2024). New Zealand's existing loading standard NZS1170.5 (Standards New

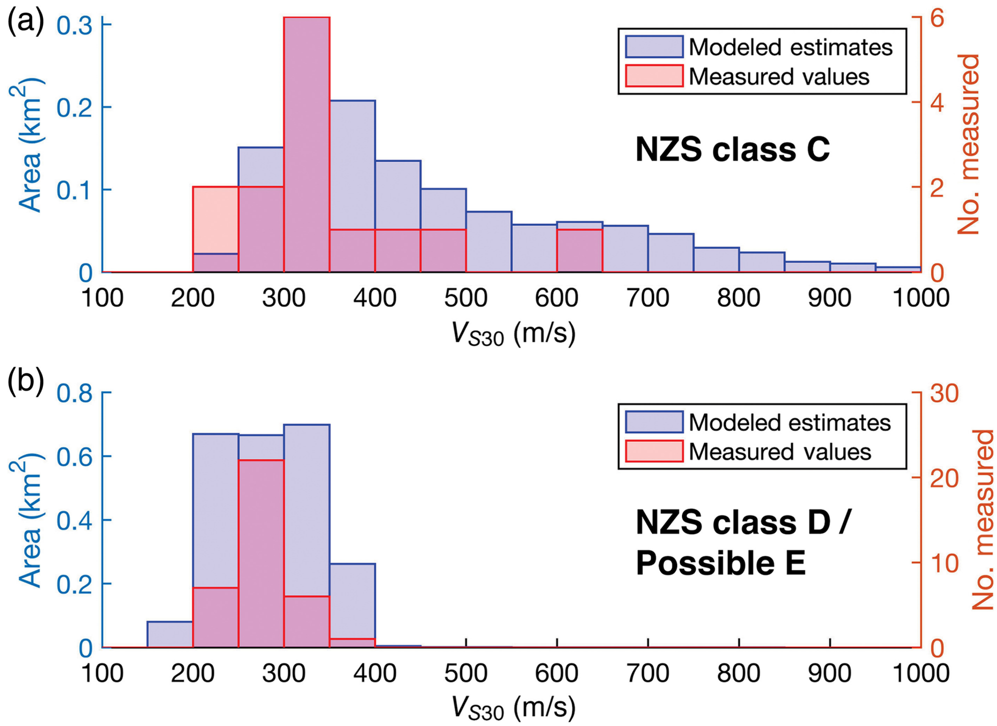

Figure 6. Relationship between the NZS class parameter and V_{S30} at central Wellington soil locations. The range of modeled and measured V_{S30} values (see Fig. 5) is shown for areas mapped as (a) NZS class C "shallow soil" and (b) NZS class D "deep or soft soil," including CentrePort. The color version of this figure is available only in the electronic edition.

Zealand, 2004) established simplified design spectra based on the uniform hazard spectra (UHS) of the NZ NSHM 2002 (Stirling *et al.*, 2002). To more fully investigate the calculated hazard changes for Wellington as relevant for design, we present an analysis of the changes associated with the NZ NSHM 2022 UHS (10% probability of exceedance [PoE] in 50 yr) with respect to the NZS1170.5 (1-in-500 yr spectra), a proxy for the equivalent NZ NSHM 2002 UHS. This is not a strict representation of changes in calculated probabilistic hazard, but it can provide insights into the implications of the NZ NSHM 2022 for future revisions to NZS1170.5. For this analysis, we draw on the maps of NZS class and V_{S30} to illustrate the effects of the change to the V_{S30} site parameter across an urban area, in addition to other influences on the calculated hazard.

In Figure 7, the ratio of spectral acceleration SA(T) from the NZ NSHM 2022 with respect to NZS1170.5 is shown in Wellington for a selection of generic V_{S30} values (further details in Kaiser *et al.*, 2022). In Figure 8, the median and range of these ratios are evaluated for a selection of spectral periods for all central Wellington soil locations (based on the mapped NZS class C and D areas and associated modeled V_{S30} estimates in Fig. 5).

For Wellington soil classes, the estimated ratios have a median between 1.2 and 1.6 across spectral periods. NZS class C has the greatest range for this ratio of between 0.6 and 2.6, reflecting the large range of possible near-surface conditions and V_{S30} values for this site class. The approximate range for NZS class D sites is 0.8 to 2.0. For class B (rock sites), the range cannot be reasonably assessed due to the lack of available V_{S30} information for rock conditions and generic V_{S30} assumptions.

The locations with the greatest changes in spectral acceleration are low V_{S30} (<300 m/s) NZS class C areas at intermediate periods of 0.5–2 s. Figure 5 shows that these conditions may be present in the central city close to the mapped C/D boundary and/or adjacent to the Aotea fault.

Site terms for Wellington

To evaluate the performance of the NSHM 2022 GMMs for central Wellington sites, we examine the site terms (systematic site-to-site residuals, $\delta S2S_s$). Site terms were calculated with respect to the ground-motion database of Hutchinson *et al.* (2022, 2023) in various studies (Kaiser *et al.*, 2022; Atkinson, 2023a; Lee *et al.*, 2023; C. A. de la Torre *et al.*, unpublished report, 2024, see Data and Resources). A complete description of the approach, following the partially nonergodic methodology of Al Atik *et al.* (2010), is presented within these references and summarized here.

The calculation of site terms ($\delta S2S_s$) is undertaken by splitting the total residual Δ (i.e., the misfit between ground-motion observation and prediction for a given event e and site s pairing) as follows:

$$\Delta = a + \delta B_e + \delta S2S_s + \delta W_{es}^0.$$

The resulting site terms, calculated for the range of spectral periods, are effectively a measure of the systematic difference of a given site to the average site once the model bias (a) and event-to-event differences (δB_e) have been taken into account. δW_{es}^0 indicates the "left over" within-event residual. The natural log (ln) of ground-motion values is used in the previous equation, such that the total residual is the natural log of the ratio of observed to predicted ground motion.

Detailed residual analyses for each residual subcomponent for each individual GMM can be found in Lee *et al.* (2023). However, as observed by that study, site-specific basin depth

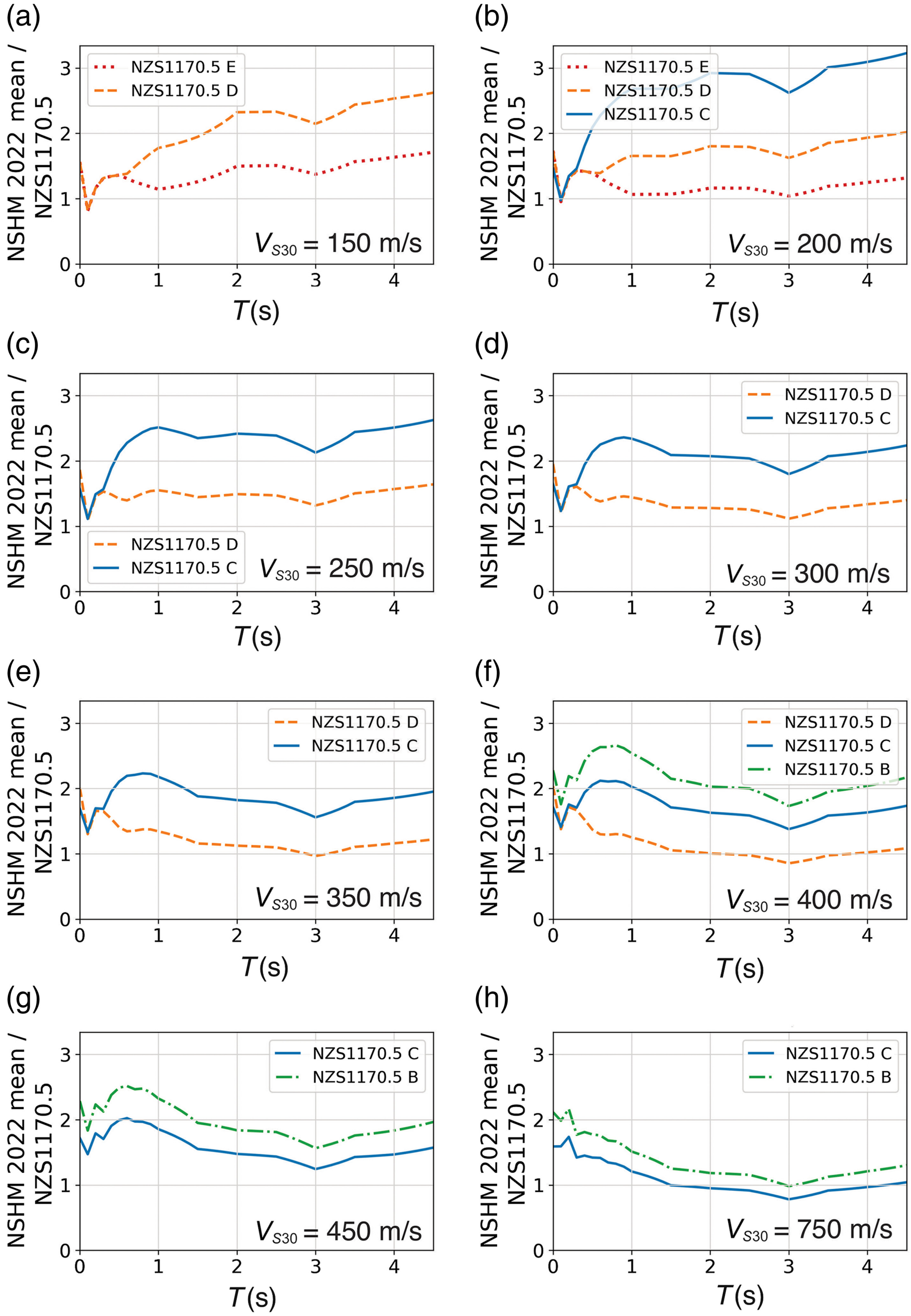

Figure 7. Ratio of the Wellington New Zealand National Seismic Hazard Model (NZ NSHM) 2022 mean uniform hazard spectra (UHS; 10% probability of exceedance [PoE] in 50 yr) with respect to the equivalent 1-in-500 yr NZS1170.5 design spectral acceleration values (Standards New Zealand, 2004). The ratios are given for a series of V_{S30} values in panels (a)–(h) and each possible NZS class mapping. The color version of this figure is available only in the electronic edition.

terms $Z_{1.0}$ and $Z_{2.5}$ were used for those analyses, whereas the 2022 NSHM implementation adopts generic V_{S30}–$Z_{1.0}$ correlations. This difference does not influence the trends or conclusions identified by Lee *et al.* (2023).

For the purposes of this Wellington amplification study, site terms were re-evaluated by C. A. de la Torre *et al.* (unpublished report, 2024, see Data and Resources) strictly following the 2022 NSHM V_{S30}–$Z_{1.0}$ implementation and combined into final NSHM weighted-model residuals. The resulting site terms (Figs. 9 and 10) effectively show any systematic deviation of a site from mean NSHM 2022 predictions that is not already accounted for by V_{S30}.

Similarly, Atkinson (2023a) calculates site terms with respect to the A22 NZ backbone model. She repeats the regression for station terms (as performed for A22 development) using an expanded NZ ground-motion database (Hutchinson *et al.*, 2023) as well as a smaller subset of Wellington regional ground-motion data. A comparison of the results confirmed that the A22 model was essentially unbiased in Wellington with respect to both path and source terms, such that the site terms can be considered a robust representation of station site response. Comparison of the A22 site terms and those for NSHM 2022 show strong similarity, which is unsurprising, given that the backbone model is a reasonable representation of the overall set of NSHM GMMs (Lee *et al.*, 2023; Bradley *et al.*, 2024).

NSHM 2022 site terms for the three Wellington subbasins of Thorndon, Te Aro, and Lower Hutt are shown in Figure 9. Mean site terms for each subbasin show similar character, with positive values (underprediction) around spectral periods of 1 s. However, there is considerable within-basin variation across individual sites. Peak residuals correlate generally

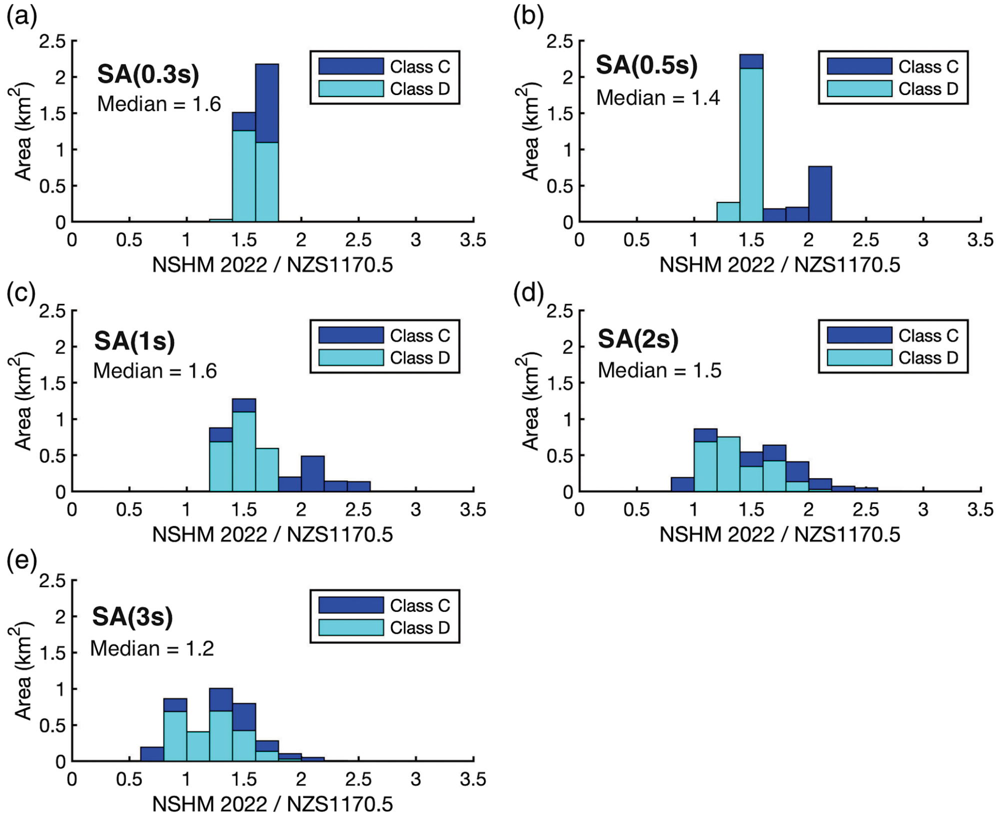

Figure 8. Changes in mean calculated hazard with the NZ NSHM 2022 with respect to the current design spectral acceleration values for central Wellington. Ratios represent the NZ NSHM 2022 UHS (10% PoE in 50 yr; Gerstenberger *et al.*, 2022, 2024) with respect to the equivalent 1-in-500 yr NZS1170.5 design spectral acceleration values (Standards New Zealand, 2004). The range of ratios for each spectral period in panels (a)–(e) arises from the update in site parameter from NZS class to V_{S30} and the complex mapping between these two parameters. The color version of this figure is available only in the electronic edition.

with T_0, which can be seen clearly when site terms are normalized by T_0 in Figure 10. Particularly in the Te Aro basin, this correlation is clear; here the amplification peaks tend to be less complex, and T_0 is also well constrained by measurements (Fig. 4a). The highest site terms at 0.5–3 s periods are observed at sites that exhibited strong amplification effects in large historical earthquakes, including during the 2016 M_w 7.8 Kaikōura and Cook Strait earthquakes (e.g., stations PIPS, TFSS, and TEPS; Holden *et al.*, 2013; Bradley *et al.*, 2018).

For comparison with other linear site-specific amplification models in later sections, we also apply a simple adjustment to render the site terms relative to the commonly used rock reference condition of $V_{S30} = 760$ m/s. Here, for each site, we add the site-to-site residual $\delta S2S_s$ to the appropriate mean GMM linear amplification function F_{lin} for station *s*. F_{lin} is calculated using the site-specific V_{S30} (equivalent to that used in the site term calculations) with respect to the $V_{S30} = 760$ m/s reference condition. The natural log of amplification values is used in the following:

$$\delta S2S_{s,\text{ref}760,} = F_{\text{lin}} + \delta S2S_s.$$

For A22 site term adjustment, F_{lin} is the linear amplification term of the Boore *et al.* (2014) GMM (BSSA14, adopted in A22). For the NSHM 2022 site term adjustments, F_{lin} represents the weighted mean of the GMCM linear amplification predictions. We also observe that the ground-motion database of Hutchinson *et al.* (2022) used in the calculations of site terms is dominated by linear ground-motion records (Stafford, 2022); thus, we can consider the site terms $\delta S2S_s$ to be applicable for linear ground motions.

Examination of Wellington basin-specific $Z_{1.0}$ in NSHM GMMs

Globally, hazard models are increasingly considering additional site parameters to V_{S30} to capture basin effects or a more nuanced site response. For example, Petersen *et al.* (2020) and Shumway *et al.* (2020) use maps of basin depth ($Z_{1.0}$) within four specific basins to provide adjustments to hazard to better capture long-period basin effects. However, they observe that this approach is only adopted for deeper basin areas and may not be suitable to capture complex amplification effects in which basin depth is shallow. In this section, we consider the use of $Z_{1.0}$ as an additional parameter for Wellington.

The $Z_{1.0}$ parameter is estimated for Wellington based on 3D geological models (Hill *et al.*, 2022) and assumed to coincide with greywacke basement depth. This is a reasonable assumption for the Te Aro and Thorndon basins, as verified by downhole V_S profiles terminating at basement depth (Kaiser *et al.*, 2019). However, there are larger uncertainties associated with $Z_{1.0}$ in the CentrePort area due to a lack of deep borehole information and the fact that strong amplification peaks indicate deeply buried sedimentary units with potentially high V_S may be present above greywacke, creating a shallow impedance contrast (Vantassel *et al.*, 2018; Kaiser *et al.*, 2019; Manea *et al.*, 2024). However, it is clear that basin-specific $Z_{1.0}$ values in central Wellington are less than those given by the generic V_{S30}–$Z_{1.0}$ correlation adopted in the NZ NSHM 2022 (Fig. 11 and Table 3).

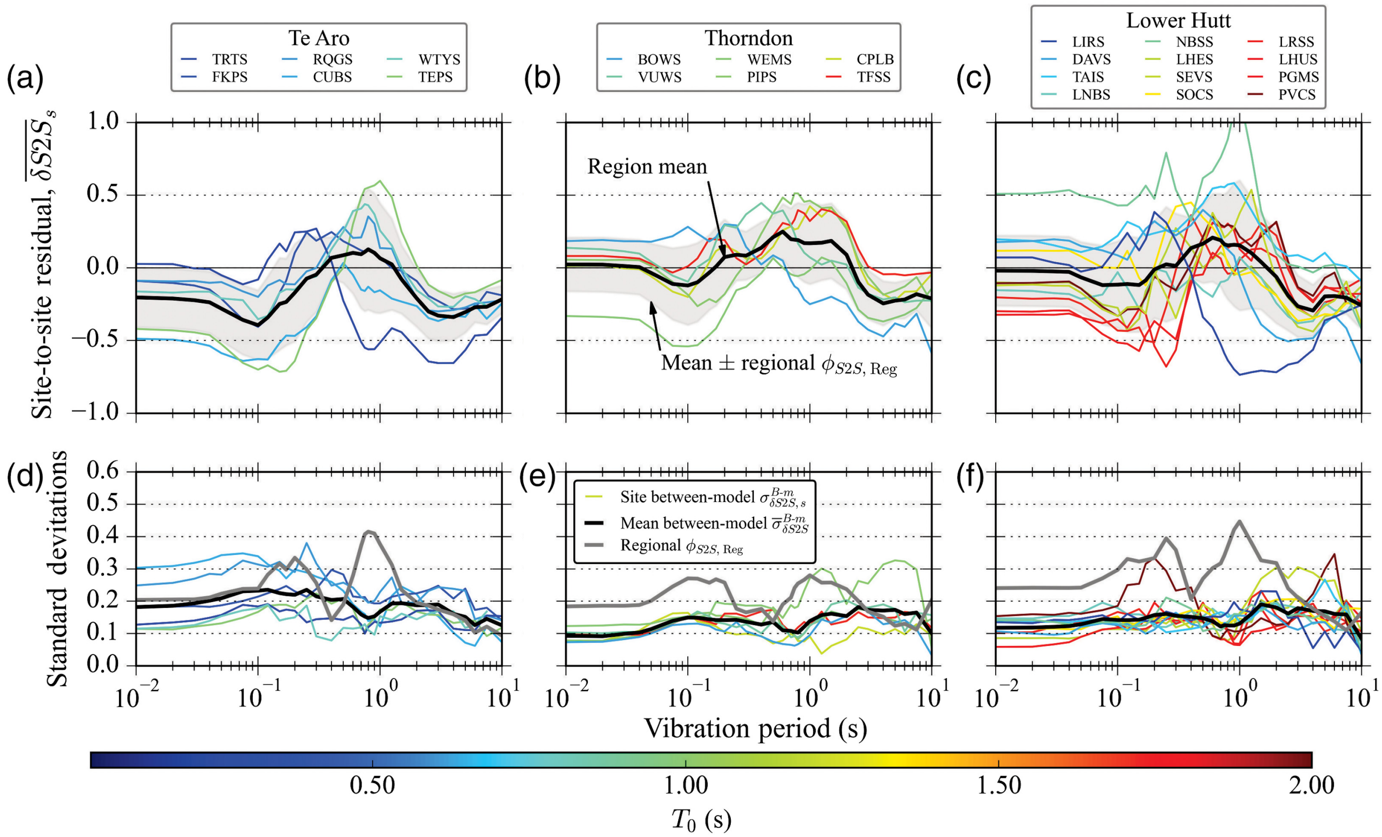

Figure 9. (a–c) NSHM 2022 station site terms and (d–f) their standard deviation (C. A. de la Torre *et al.*, unpublished report, 2024, see Data and Resources) grouped by Wellington subbasins of Te Aro, Thorndon, and Lower Hutt. The regional subbasin mean values are shown as thick black lines, and individual stations are colored by their fundamental site period T_0. For individual stations, the site term represents the weighted average across all ground-motion models (GMMs) considered in the NSHM. The color version of this figure is available only in the electronic edition.

Although the use of basin-specific Z1.0 is appealing to better capture long-period shaking generated in deep basins, its applicability in shallow basins such as Wellington, in which strongly peaked amplification is observed at intermediate periods, needs careful consideration. There are both practical and scientific reasons not to adopt the use of this parameter in the 2022 NSHM.

First, as found by Atkinson (2022) for the New Zealand dataset, once correction for V_{S30} is applied within NSHM GMMs, systematic site-to-site residuals show no overall significant bias or correlation with other site parameters, for example, $Z_{1.0}$, $Z_{2.5}$, or T_0. This supports the use of V_{S30} as the sole site parameter within this GMM. It is also an important observation for the application of GMMs to New Zealand generally, but it does not preclude further exploration of basin depth parameters in future GMM development or for regional- or basin-scale adjustments. We observe that $Z_{1.0}$ and $Z_{2.5}$ are very poorly characterized and constrained in New Zealand (Wotherspoon *et al.*, 2024), limiting the aforementioned analysis. The difficulty in measuring these parameters also currently precludes their practical application in hazard assessment.

Second, for the Wellington basin (and other shallow basins), the adoption of site-specific $Z_{1.0}$ in current crustal GMMs has the general effect of reducing GMM predictions at intermediate-to-long periods (e.g., Kaiser *et al.*, 2022). To better understand the impact of using site-specific basin depth parameters for the two Wellington subbasins of Thorndon and Te Aro, we performed a hazard sensitivity analysis. For this analysis, we adopt two generic sites for each subbasin with a V_{S30} of 250 m/s and $Z_{1.0}$ depths corresponding approximately to deeper locations within the Te Aro and Thorndon basins. Figure 12 shows the result of hazard calculations performed with: (1) the California-based V_{S30}–$Z_{1.0}$ correlations; and (2) basin-specific $Z_{1.0}$ and $Z_{2.5}$ values. Only the crustal GMMs in NZ NSHM 2022 include $Z_{1.0}$ or $Z_{2.5}$ as predictor variables (see the Treatment of Site Effects in NZ NSHM section). Thus, comparisons are made for all sources as well as for crustal sources only. Overall, there is no significant change in computed hazard for 10% PoE in 50 yr between the two choices of $Z_{1.0}$. For 2% PoE in 50 yr, there is a slight lowering of the computed hazard, mainly for intermediate and longer periods (>1 s). As expected, the difference in computed hazard is larger when only shallow crustal GMMs (and sources) are considered. Although the reduction in calculated hazard at long periods (>3 s) may be justifiable, given the lack of observed long-period amplification (see next sections and

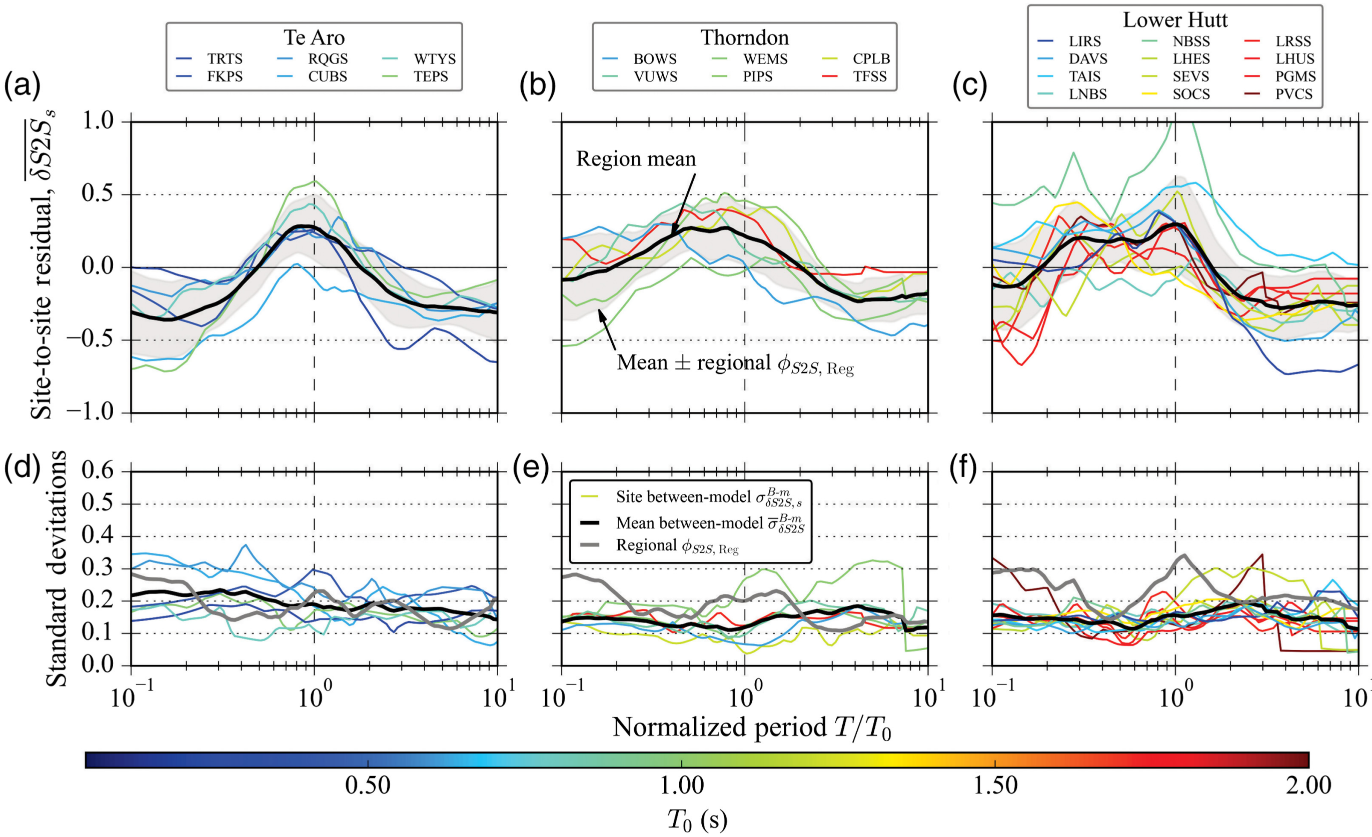

Figure 10. NSHM 2022 station site terms (C. A. de la Torre *et al.*, unpublished report, 2024, see Data and Resources) as for Figure 9, plotted normalized by the fundamental site period (T/T_0). (a–c) Site terms and (d–f) their standard deviation are grouped by the Wellington subbasins of Te Aro, Thorndon, and Lower Hutt. The regional subbasin mean values are shown as thick black lines, and individual stations are colored by their fundamental site period T_0. For individual stations, the site term represents the weighted average across all GMMs considered in the NSHM. The color version of this figure is available only in the electronic edition.

Atkinson, 2023a), the slight reduction at intermediate periods (1–2 s) in which strong basin effects are observed is not desirable.

We conclude that the inclusion of basin-specific $Z_{1.0}$ for Wellington in the NZ NSHM 2022 (i.e., in combination with the current ergodic site amplification factors) is not warranted, because it does not improve the characterization of observed basin amplification effects. However, ground-motion residuals for the NZ NSHM 2022 GMM implementation in central Wellington do appear to be correlated with basin depth parameters (in particular T_0) even after the application of V_{S30} (C. A. de la Torre *et al.*, unpublished report, 2024, see Data and Resources; Figs. 9 and 10). Hence, the use of basin depth or related terms should be explored in the development of future region- or basin-specific adaptations to GMMs.

The GMMs adopted in NZ NSHM 2022 and their associated sigma models represent statistical averages over a large range of basin conditions globally. Basin conditions found in Wellington are likely not representative of the "average basin" within the underpinning databases that guided NGA-West2 GMM development. For example, the Wellington basin contains a significant thickness of Quaternary sediment directly overlying Rakaia terrane greywacke at a relatively shallow depth. This unconformity creates conditions for a strong impedance contrast that amplifies seismic waves at intermediate periods. Furthermore, the steep-sided basin edges and relatively confined nature of the Wellington basin also increase the amplitude of amplification (see Lee *et al.*, 2022). Hence, the site response in central Wellington may differ significantly from that in basins that have a broader structure and/or a more gradational velocity profile with depth.

The velocity profile, and hence the V_{S30}–$Z_{1.0}$ relationship, for the Wellington basin appears more typical of that derived for Japan than for California (Fig. 11). It has long been recognized that such regional differences in the velocity profile, for the same value of V_{S30}, impact the applicability of GMMs (e.g., Atkinson and Boore, 2003; Kamai *et al.*, 2016), and some GMM developments for seismic hazard mapping have made explicit adjustments to account for these effects (e.g., Atkinson and Adams, 2013).

This trend toward amplification at intermediate periods, driven by impedance contrasts at relatively shallow depth, may also hold for other basins in New Zealand, given common geological conditions; however, this requires

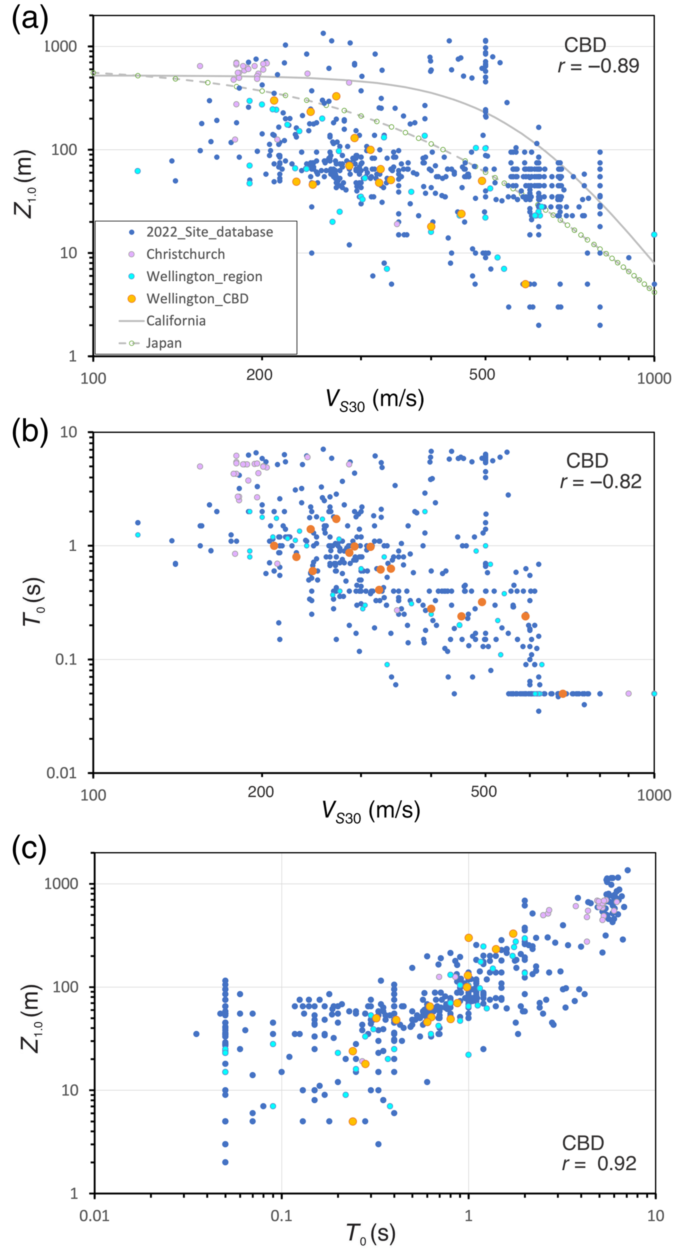

Figure 11. Wellington and New Zealand site parameter relationships based on Wotherspoon *et al.* (2022). (a) V_{S30}–$Z_{1.0}$ data compared to the correlations of Chiou and Youngs (2014) for California and Japan. (b) V_{S30}–T_0 data. (c) T_0–$Z_{1.0}$ data. V_{S30} and $Z_{1.0}$ parameters for New Zealand stations are generally poorly constrained (Wotherspoon *et al.*, 2022, 2024). Higher quality estimates are available in Christchurch, the Wellington Region (including Lower Hutt), and central Wellington (CBD) (e.g., Lee *et al.*, 2018; Wotherspoon *et al.*, 2020; Hill *et al.*, 2022), and these regions are highlighted in orange, light blue, and pink, respectively. Some parameters for the Wellington CBD were updated in this study (as detailed in Table 3). The correlation coefficients (*r*) for Wellington CBD are provided within the panels. The color version of this figure is available only in the electronic edition.

confirmation through a more robust determination of site parameters across the country. The basin below Christchurch (and Canterbury) is known to be much deeper, with a T_0 of ~5–7 s (Stolte *et al.*, 2023), and appears typical of the global average represented in mean GMM predictions.

In summary, the use of basin depth terms ($Z_{1.0}$, $Z_{2.5}$, and T_0) in New Zealand needs further region- and basin-specific consideration. For example, GMMs may benefit from regional adaptation of ergodic site models to best reflect New Zealand conditions, and/or basin-specific site models (nonergodic models) could be implemented to better capture local amplification.

LOCAL AMPLIFICATION MODELS FOR CENTRAL WELLINGTON

Linear amplification models

A set of site-amplification models based on different approaches have been implemented for central Wellington under the NZ NSHM program. Here, we briefly introduce the models; further details of the model derivation are contained in the underpinning technical reports and articles listed in Table 1. The amplification models we consider and compare in Figure 13 are:

1. Mean NSHM 2022 amplification curves derived from global or regional backbone GMMs, and weighted according to the GMCM logic tree (Bradley *et al.*, 2024).
2. Site terms derived from residual analysis, including those for the full NSHM 2022 implementation (adjusted terms of C. A. de la Torre *et al.*, unpublished report, 2024, see Data and Resources) and those derived for the A22 backbone model (Atkinson, 2022, 2023a). For more detail, see the Site terms for Wellington section and underpinning references.
3. Response spectral ratios (RSRs) of de la Torre *et al.* (2022, 2023) for a set of historical earthquakes exhibiting weak-to-moderate shaking intensity. RSR is defined as the ratio of the pseudoacceleration response spectra (5% damped) at a given soil station with respect to a reference, in this case, the commonly used reference station POTS (discussed in the following section).
4. Hybrid standard spectral ratios (SSRhs) were calculated for central Wellington by Manea *et al.* (2024) based on the adjusted methodology of Perron *et al.* (2018). The SSRh is calculated for a given soil station (*S*2) with respect to the rock reference (RA) by combining the classical standard spectral ratio (SSR; Borcherdt, 1970) calculated from earthquake data at an intermediate soil reference site within the basin (*S*1) and the soil-to-soil station ambient noise-based SSR (SSRn), as follows:

$$\mathrm{SSRh}_{\frac{S2}{RA}}(f) = \mathrm{SSR}_{\frac{S1}{RA}}(f) \times \mathrm{SSRn}_{\frac{S2}{S1}}(f).$$

Consistent with the calculation of SSR, the SSRh are based on Fourier amplitude spectra ratios; hence, although SSRh could be expected to highlight the same amplification features as ratios based on response spectra (models 1–3),

TABLE 3
Summary of GeoNet Strong-Motion Station Site Parameters in Central Wellington

Station	V_{S30}	V_{S30} Quality	$Z_{1.0}$	$Z_{1.0}$ Quality	$Z_{1.0}$ (GMCM Default)	T_0	T_0 Quality
POTS	453	Q1	24	Q1	288	0.24	Q1
PIPS*	210	Q1	300	Q3	507	1	Q1
CPLB†*	244	Q1	233	Q3	494	1.4	Q1
RQGS	246	Q2	46	Q2	493	0.6	Q1
TFSS*	271	Q1	330	Q3	479	1.7	Q2
VUWS	286	Q1	76	Q2	469	0.87	Q2
TEPS*	292	Q1	130	Q2	465	1	Q1
WEMS†*	312	Q1	100	Q3	449	1	Q2
FKPS*	323	Q1	48	Q2	440	0.41	Q2
BOWS†	325	Q1	65	Q1	438	0.62	Q2
CUBS†	339	Q2	51	Q2	425	0.63	Q2
TRTS†	400	Q2	18	Q2	356	0.28	Q1
WCFS†	589	Q2	5	Q2	135	0.24	Q2

Site parameters are consistent with the database of Wotherspoon *et al.* (2024), except where updated in this study as indicated in the following. Quality estimates (following Kaiser, Van Houtte, *et al.*, 2017) show which parameters are Q1 = well constrained, Q2 = reasonably constrained, and Q3 = poorly constrained. $Z_{1.0}$ (GMCM default) values are derived from V_{S30} using the default California-based V_{S30}–$Z_{1.0}$ correlation (Chiou and Youngs, 2014) adopted in the NZ NSHM 2022.
GMCM, ground-motion characterization model; and NZ NSHM, New Zealand National Seismic Hazard Model.
*$Z_{1.0}$ updated in this study by adopting greywacke basement depth values from the updated 3D geological model of Hill *et al.* (2022).
†V_{S30} updated in this study with estimates from the Wellington V_{S30} model and measurements presented in Figure 5.

the definition of amplification is not strictly equivalent. The extensive dataset of ambient noise measurements in Wellington allows SSRh ratios to be calculated on a dense grid through the central city.

5. Three-dimensional physics-based ground-motion simulations (Lee *et al.*, 2022). Simulations of ground-motion amplification within the Wellington basin were performed for a set of six historical earthquakes ranging from M_w 5.5 to 6.6. Key advances in this study included (1) extending the comprehensive physics-based (i.e., deterministic) simulations to higher frequencies (reliably up to 2 Hz; down to 0.5 s) by employing a finer grid resolution and (2) testing multiple more realistic representations of the 3D basin geometry (Hill *et al.*, 2022; Stronach and Stern, 2021).

Each of these modeling approaches has strengths and limitations due to the underlying methodology and input, as summarized here in Kaiser *et al.* (2022) and identified in the relevant references.

Reference station POTS

To compare amplification models, the common rock reference condition of V_{S30} 760 m/s is chosen. For the purposes of comparison, site terms are adjusted to represent linear amplification relative to this reference condition, as described in the Site terms for Wellington section.

Empirical RSR and SSRh amplification ratios are calculated with respect to the commonly used reference station POTS. POTS is located at the basin edge above shallow, stiff soil and has a measured V_{S30} of ~453 m/s (Wotherspoon *et al.*, 2024). Despite its shallow soil cover, the station has a well-studied flat site response; it may also be affected by deamplification effects associated with the steep hill rising above the station. Figure 13a confirms that the observed site response of station POTS is less pronounced than expected for a typical ~450 m/s soil site (i.e., compared to the solid black line) and is close to 1. In other words, its amplification is similar to that predicted for the reference condition. This conclusion supports the use of RSR with respect to station POTS as a robust measure of linear amplification with respect to typical soft rock site conditions represented by V_{S30} 760 m/s.

Physics-based simulation results are also included for comparison in Figure 13 at the deep soil sites, although the reference conditions are not strictly equivalent. Furthermore, the grid spacing combined with the minimum velocity of 500 m/s adopted in the simulations means the influence of softer near-surface sediments is not well captured (as detailed in Lee *et al.*, 2022). Nevertheless, the simulations can provide useful insights into the generation of 3D basin effects and how they can be interpolated across the city.

Comparison of site-specific linear amplification models at central Wellington sites

In this section, we compare and discuss the mean amplification model results at 13 central Wellington strong-motion stations (Fig. 13). A summary of the station site parameters V_{S30}, $Z_{1.0}$, and T_0 is given in Table 3.

Overall, the mean linear amplification factors in central Wellington at individual sites are consistent between various methods. Site terms for the NSHM 2022 (including for A22) and RSR are compatible across all of the central Wellington stations, confirming that RSR with respect to POTS provides a relatively unbiased representation of site response relative to rock. Amplification ratios from SSRh and simulations also

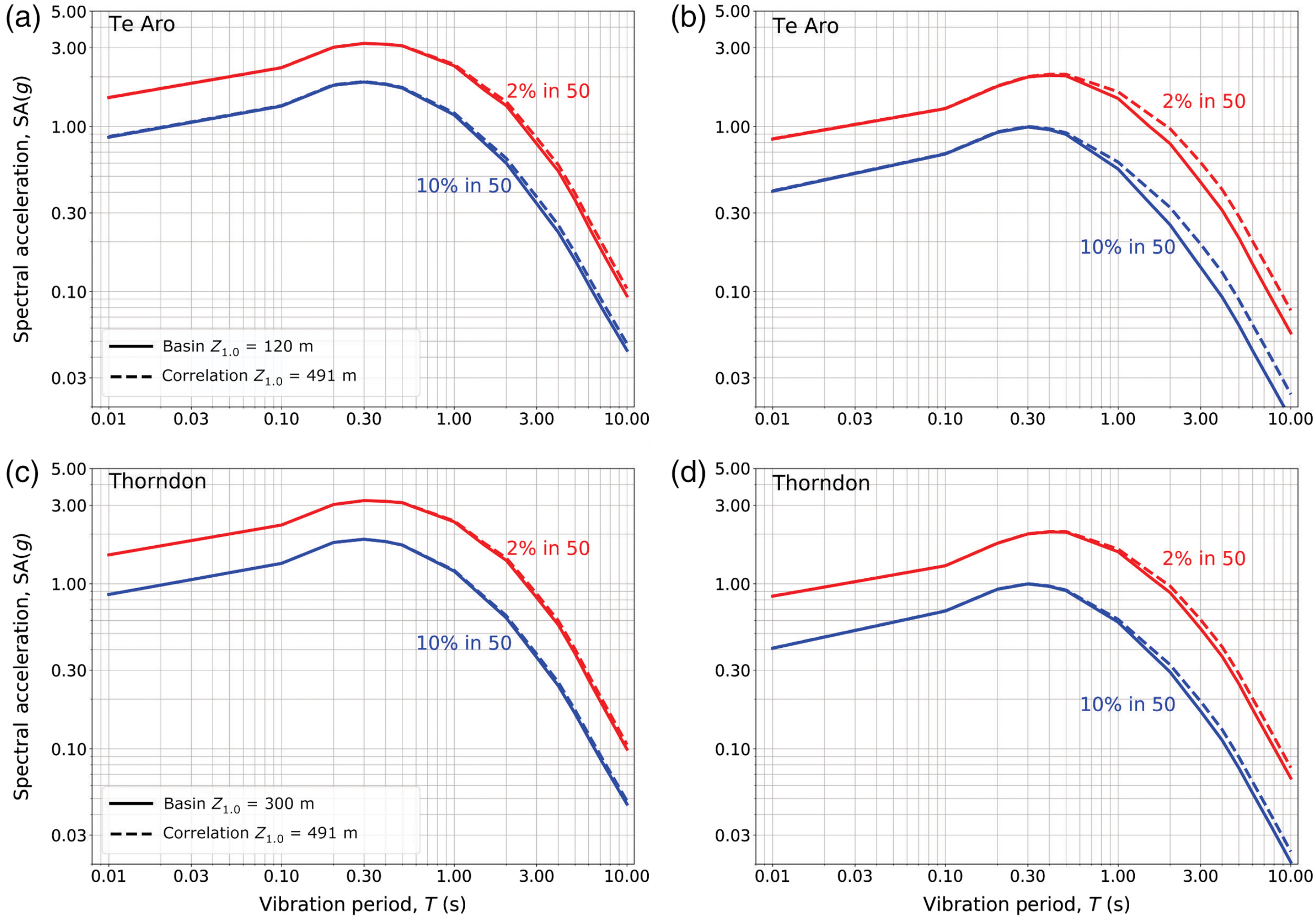

Figure 12. Plots showing the effect on UHS of adopting basin-specific $Z_{1.0}$ estimates for Wellington within the NZ NSHM 2022 ground-motion modeling framework. Hazard curves are shown for a representative soft soil site in Te Aro: (a) when all sources are considered for hazard computation; (b) when only crustal sources are considered; and in Thorndon; (c) when all sources are considered for hazard computation; and (d) when only crustal sources are considered. Two cases are compared: basin-specific $Z_{1.0}$ (solid curve) and a generic $Z_{1.0}$ using the California-based correlation currently adopted in the NZ NSHM 2022 (dashed curve). The hazard is computed for a single source branch, along with the full ground-motion characterization model (GMCM; Bradley *et al.*, 2024) logic tree. The color version of this figure is available only in the electronic edition.

generally show similar characteristics to site terms, although the amplitude and period of amplification peaks may differ. Although results for these methods are not considered as robust, they do not rely on station earthquake recordings and hence provide useful interpolations at high spatial resolution across the basin.

For some stations, the observed (linear) amplification is reasonably well approximated by NSHM GMM mean predictions, for example, at stations WEMS, FKPS, CUBS, and WCFS. These sites are all located on stiffer near-surface soils with $V_{S30} > 300$ m/s.

For another set of sites, shorter period amplification peaks (<1 s) are present that are somewhat higher and more pronounced than NSHM GMM mean predictions, for example, VUWS, BOWS, TRTS, and RQGS. These are all shallower sites, with the peak amplification period corresponding roughly to T_0. All of these sites, with the exception of RQGS, also have an estimated $V_{S30} > 300$ m/s.

The remaining soil stations (e.g., PIPS, CPLB, TFSS, and TEPS) have strongly peaked amplification observed around the fundamental site period (1–2 s) that is underpredicted by mean NSHM GMMs. These stations are all situated on mapped fill, located adjacent to waterfront areas with $V_{S30} < 300$ m/s, and all are located in deeper parts of the basin; the only other deep soil site is WEMS, which has stiffer material lying at relatively shallow depths, implying it has a more gradational V_S profile above rock.

Regional V_{S30} scaling

Although V_{S30} scaling included in NSHM GMMs is generally applicable to New Zealand (Lee *et al.*, 2023; Atkinson, 2023b), specific subregions or basins may exhibit V_{S30} scaling that is different from the mean behavior. To investigate whether this is true in the Wellington basin, Atkinson (2023a) derives regional V_{S30} scaling based on the Wellington data subset

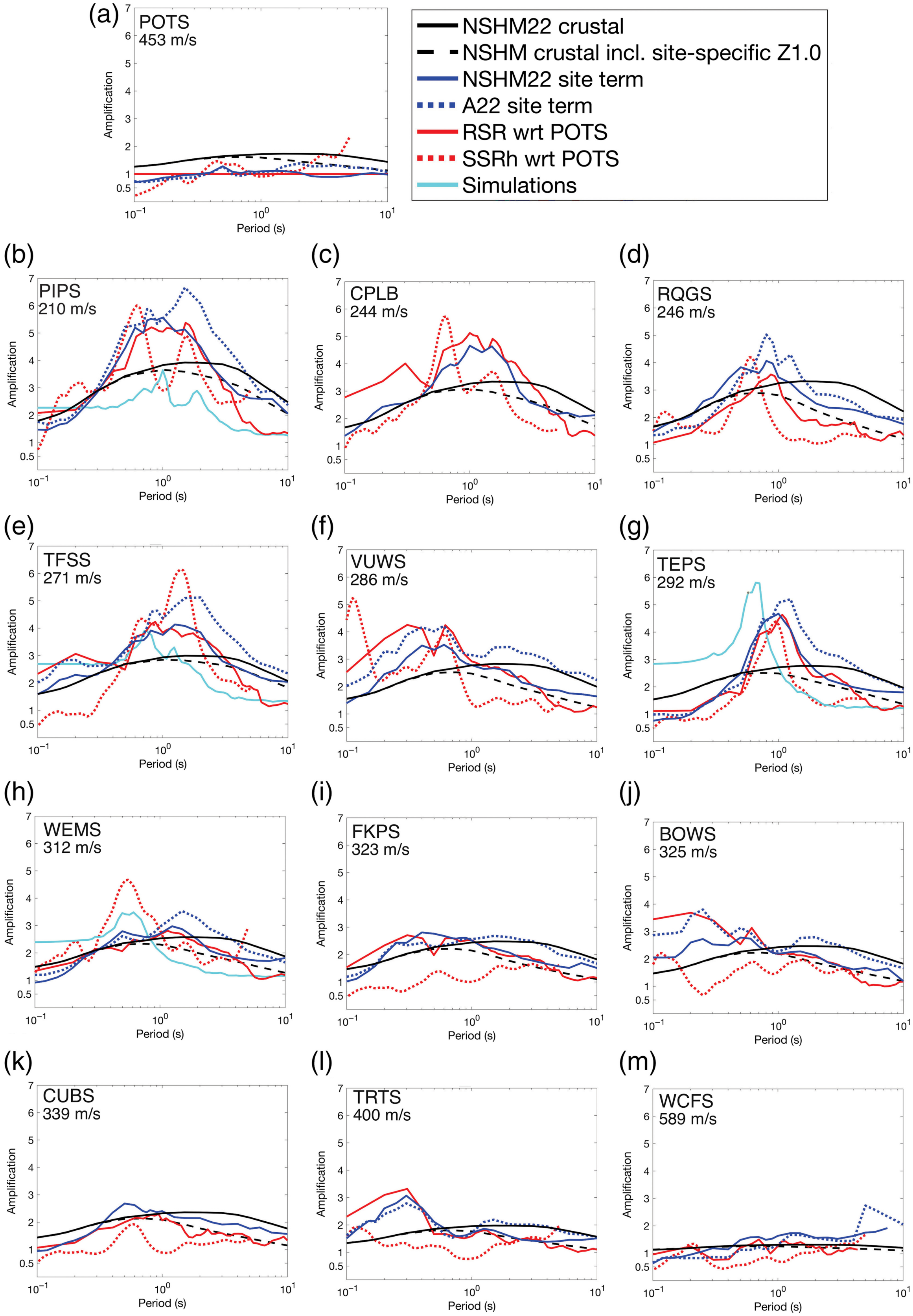

Figure 13. Comparison of linear site amplification models shown for each central Wellington strong-motion stations separately in (a) to (m). Mean values are shown for each of the models detailed in the Linear amplification models section. Weighted mean site models from the NZ NSHM 2022 GMCM crustal logic tree are shown for both the NSHM 2022 implementation (solid black lines) and when using a site-specific $Z_{1.0}$ estimate from Table 3 (black dashed lines). Station names and V_{S30} values from Table 3 are shown at the top of each figure. The color version of this figure is available only in the electronic edition.

and sites spanning the wider Wellington region outlined in Figure 1. She observed some general differences, including more strongly peaked amplification with greater amplitudes around ~1 s, but generally lower amplitudes at spectral periods 0.5> and >2 s. However, for the region as a whole, differences in amplitude at the peak were small (~10%), and the application of regional V_{S30} scaling did not significantly improve the model bias. These regional features appear to be exaggerated for the subset of well-characterized softer sites (<300 m/s) highlighted in this study of central Wellington. The regional features are also apparent in the subbasin of Lower Hutt (see Figs. 9 and 10), and further detailed research is being undertaken in this area.

Physics-based 3D ground-motion simulations

Other features of the observed amplification have been interpreted through the simulations of Lee *et al.* (2022), who identified several 3D effects associated with the Wellington basin structure, including (1) basin-edge and wave-guide effects along the Te Aro subbasin that enhanced amplification (e.g., station TEPS), (2) consistently large amplifications in the CentrePort area (e.g., station PIPS), and (3) potentially complex amplification patterns within the Thorndon subbasin due to a combination of concave and convex features of the subsurface bedrock topography.

The analyses also highlight the limitations resulting from simulation spatial resolution, in which impedance effects could not be adequately modeled at stations with shallower basin depth, although the level of amplification and broad spectral amplification peaks were well captured at some deeper basin sites (e.g., PIPS and TFSS). The use of a generalized 1D velocity profile within the basin-specific basement geometry also led to a mismatch of the peak period of amplification at some sites (e.g., TEPS). Further improvements can be made with higher spatial-resolution simulations and the inclusion of a more detailed *S*-wave velocity structure, as well as the investigation of effects for larger earthquake scenarios.

Nonlinear soil effects

Consideration of nonlinear effects is important for Wellington, given that high intensities of shaking dominate the hazard. Although these effects are strongest at short periods (<1 s), they are also expected to a lesser degree at intermediate spectral periods of interest for basin response in Wellington (0.5–2 s). The Wellington ground-motion database is dominated by low shaking intensities, representing approximately linear site response (Stafford, 2022; Hutchinson *et al.*, 2023). The highest shaking recorded in Wellington to date (PGA ~0.27*g*) occurred during the Kaikōura earthquake, in which a small component of nonlinearity was observed at the softest soil stations (de la Torre *et al.*, 2023).

A case study of nonlinear effects using numerical simulation approaches at nine Wellington strong-motion sites was undertaken by de la Torre *et al.* (2022, 2023). The study explored results from different shear-wave velocity (V_S) profiles, constitutive models, and modeling approaches to quantify the model sensitivity and modeling uncertainty. Importantly, this study also develops a method for adjusting linear site amplification estimates from weak motion observations with these nonlinear site-response analyses.

Results showed that for soft sites subjected to strong ground motions, there may be a decrease in amplification with increasing intensity for periods up to approximately 2 s. However, at stiffer sites, where lower levels of basin amplification are observed, this is true only for short periods, and there may even be an increase in amplification at longer periods (1–3 s) when nonlinearity is considered due to softening of the soil profile.

In addition, it was found that V_{S30}-based empirical nonlinear site amplification models (e.g., Seyhan and Stewart, 2014) deviated from the results of this study at large strains. This could be partially explained by the fact that such empirical models are poorly constrained due to the limited number of high-intensity observations. Moreover, such V_{S30}-based nonlinear soil response models also invoke the assumption of ergodicity, whereas, in reality, the phenomenon may vary from one site to another. However, the application of such global models provides a first-order approximation of site-specific nonlinear effects. Where strong amplification peaks are present at the periods of interest, these ergodic adjustments may be poorer than for those sites that are better represented by mean GMM predictions. However, there also remains considerable uncertainty in site-specific numerical modeling of these effects. The treatment of nonlinear effects is a key area of uncertainty in considering the application of basin-specific amplification models in the future NSHM, particularly for Wellington and other shallow basins in high seismic hazard areas.

Overall, our analysis in this section shows that the mean linear amplification factors in the Wellington basins at individual sites are consistent between various methods. Clearly, the discrepancy between various methods reflects the epistemic uncertainty associated with such amplification factors. Nevertheless, the within-site uncertainty at shorter periods (<2 s) due to high-intensity motions remains large, and is currently difficult to constrain with the data and methods available.

DISCUSSION AND FUTURE DIRECTIONS

The change in site parameter from NZS class to V_{S30} in the NZ NSHM 2022, coupled with a general increase in calculated NZ seismic hazard, has the potential to strongly influence site-specific hazard values. For example, a general increase in calculated hazard by a factor of ~1.5 is expected for Wellington when compared to the current NZS1170.5 loading standard equivalent design spectra (based on the 2002 NZ NSHM). However, site-specific hazard increases may be negligible or as high as a factor of 2.6, depending on the local site conditions and the period of interest (Fig. 8). For most New Zealand regions, the full extent of local changes is less clear due to the lack of robust regional V_{S30} characterization. However, we would expect the findings from Wellington to apply generally, with large ranges of calculated hazard changes and potentially large changes at softer NZS class C sites. The analysis also highlights the sensitivity of hazard models to the site models adopted in underpinning GMMs.

Quantifying the uncertainties associated with the treatment of site response is a critical component to consider in seismic hazard models. We observe that the between-station variability of site terms across NZ remains high in the range of 0.3–0.75, depending upon the vibration period and event type (Atkinson, 2022; Stafford, 2022; Lee *et al.*, 2023). Several factors may contribute to these findings, including unaccounted-for variations in regional attenuation; however, the lack of measured V_{S30} at the recording station sites is a major contributor to uncertainty. Previously, the analysis of Kaiser, Van Houtte, *et al.* (2017) has suggested that a reduction in average site-to-site residuals $\delta S2S_s$ can be achieved through the use of higher-quality V_{S30} characterization. The Wellington case study has also illustrated how higher-quality V_{S30} characterization (compared to coarse national V_{S30} model estimates) leads to improved fits between generic mean GMM predictions and local site-specific amplification models. This, in turn, has enabled us to more accurately pinpoint locations (e.g., deeper basin sites with $V_{S30} < 300$ m/s) where the strongly peaked basin response is truly underpredicted by mean GMM site models. The characterization of V_{S30} is clearly a potential area of improvement for future NSHMs, along with the consideration of regional adjustments and/or partially nonergodic models to better capture local and regional effects (e.g., Al Atik *et al.*, 2010; Bradley, 2015; Ameri *et al.*, 2017; Baltay *et al.*, 2017; Hassani and Atkinson, 2017a,b; Kotha *et al.*, 2017; Çağnan and Akkar, 2019).

Improvements in the characterization of the Wellington basin have allowed the comparison of multiple approaches to model linear amplification, producing relatively consistent results at a given site with a component of epistemic uncertainty (Fig. 13). Site terms and RSR with respect to station POTS give similar results, both providing consistent estimates of linear site amplification. SSRh methods can be useful to extend these observations to new locations, although with lower accuracy. The utility of SSRh lies in its ability to map spatial amplification patterns using dense observational datasets (as discussed in Manea *et al.*, 2024). Physics-based modeling methods can also be a useful tool to provide insights into the generation of more complex 3D basin effects and map spatial patterns (Lee *et al.*, 2022).

Shallow basins with complex subsurface topography, such as the Wellington basin, pose a particular challenge for site response modeling. Because of their small spatial scale and shallower depth, amplifications are generated at short to intermediate periods and vary over short spatial scales. When strong impedance contrasts and/or steep-sided basin geometry are present, 3D effects can produce strong amplification peaks at these periods that are not well captured by mean ergodic GMM predictions. Furthermore, unlike for long-period basin response, special consideration of the effects of soil nonlinearity at high shaking intensities is needed.

At present, default values of the basin depth parameter ($Z_{1.0}$) are used in the NSHM GMCM 2022 framework, and the use of site-specific $Z_{1.0}$ is not adopted for Wellington or elsewhere. For Wellington generally, the use of site-specific $Z_{1.0}$ within this framework slightly reduces the amplitude of ground-motion predictions (and hazard) at intermediate periods. Thus, at stations where strong basin amplification peaks occur at these periods, adopting site-specific $Z_{1.0}$ is shown to exacerbate underprediction by mean GMMs. However, we observe that it does better align the period of predicted spectral amplification peaks with observations by reducing amplification at longer periods (see Fig. 13). The analysis of $\delta S2S_s$ residuals (Fig. 10) similarly highlights the correlation between the period of positive residual peaks and the parameter T_0, which is strongly correlated with $Z_{1.0}$ in Wellington (see Fig. 11). These observations encourage the future exploration of the use of basin depth parameters (e.g., $Z_{1.0}$ or T_0) coupled with the development of tailored modeling approaches for such shallow basins.

For Wellington, the further development of basin-specific site amplification models can focus on (1) testing linear amplification models and extending their application beyond seismic station locations; (2) further consideration of amplification at high intensities of shaking, including nonlinear effects; and (3) quantification of the within-site uncertainty (sigma) for these models, including at high intensities of shaking.

It is also worth observing that national analysis shows that central Wellington site terms are not anomalous, and a similar magnitude of residuals is found elsewhere in New Zealand (e.g., Atkinson, 2023a; Lee *et al.*, 2023). In other words, the degree of systematic residual site amplification effects observed in Wellington is relatively common in other basin locations.

Ongoing and future NSHM research in New Zealand will consider both regional adjustments to existing GMMs and the potential of nonergodic models. The generally poor characterization of V_{S30} in New Zealand currently limits any such advanced approaches. Further development of site characterization and ground-motion databases, as well as basin-specific 3D models, is required for these advanced modeling techniques to be fully explored. One important aspect currently under further investigation is the impact of the uncertainties in potential predictor variables V_{S30}, $Z_{1.0}$, and $Z_{2.5}$ on average site terms and hence on repeatable effects such as between-station variability. This investigation is also of significant importance for site-specific hazard analysis.

It is worth emphasizing (and also valid globally) that the uncertainty in characterizing site effects in NSHMs often maps to other aspects of ground-motion modeling (and parameters), such as the estimation of magnitude, source corner frequency, and path-related anelastic attenuation. This poses a significant challenge for the treatment (and hence quantification) of (aleatory and epistemic) uncertainties in seismic hazard. Improving the characterization of V_{S30} and also V_S at greater depths is therefore a priority that is expected to greatly benefit future New Zealand research and application.

CONCLUSIONS

We present an overview of the treatment of site effects in NZ NSHMs, including a case study of basin effects in central Wellington conducted by the site/basin working group of the NZ NSHM program.

To underpin our analysis of site effects in the Wellington basin, we have developed a new regional 3D geological and shear-wave velocity model (Hill *et al.*, 2022), and an updated set of geotechnical maps for central Wellington (T_0, NZS class, V_{S30}). These maps are not routinely available in New Zealand, making central Wellington the ideal study area to test and understand the application of the NZ NSHM 2022.

The NZ NSHM 2022 revision includes a change in site parameters from the NZS class to V_{S30}. For central Wellington, we illustrate the implications of this change by comparing the 2022 calculated hazard (UHS, 10% PoE in 50 yr) with respect to the equivalent design spectra in the NZS1170.5 loading standard. The NZ NSHM 2022 leads to an increase in calculated hazard by median factors of 1.2–1.6 times higher (depending on spectral period) at soil sites within central Wellington. However, a large range of increases (~0.8–2.6 times higher) is expected across these sites, depending on the mapped site parameters. The largest increases are associated with intermediate spectral periods (0.5–2 s) at softer class C sites with $V_{S30} < 300$ m/s. This analysis also highlights the sensitivity of hazard models to the primary site parameters used in underpinning GMMs.

We also summarize Wellington site terms for the NSHM 2022 (Atkinson, 2023a; C. A. de la Torre *et al.*, unpublished report, 2024, see Data and Resources), which represent the systematic variations from an "average" site when mean GMM predictions are compared to observations. Site terms in central Wellington exhibit positive values of up to ~0.5 ln units (factor of ~1.6) for several softer sites (V_{S30} 200–300 m/s), which also tend to be located in deeper parts of the basin. The site-term positive peaks appear at periods that are generally well correlated with the fundamental site period (T_0).

We compare site terms with a set of linear amplification models derived from spectral ratios (RSR [de la Torre *et al.*, 2022, 2023] and SSRh [Manea *et al.*, 2024]) and physics-based simulations (Lee *et al.*, 2022). Results show that site-specific mean values are generally compatible across modeling approaches. Although SSRh and simulation-based models are considered less robust than direct site-specific empirical estimates, they are useful tools in mapping and understanding amplification characteristics in which seismic stations are sparse. Physics-based simulations also highlight the presence of 3D basin effects that increase ground-motion amplification in areas of Wellington and lead to complex spatial patterns.

The Wellington study highlights the challenge of capturing complex basin amplification effects in shallow basins, particularly where strongly peaked amplification occurs associated with strong shallow impedance contrasts. The use of site-specific basin depth ($Z_{1.0}$) in the 2022 NSHM GMMs does not better capture the strong amplification peaks and, in fact, somewhat exacerbates the underprediction of their amplitude. However, basin depth terms (T_0 and $Z_{1.0}$) are clearly correlated with the period of the observed amplification peaks in Wellington, encouraging further investigation of their potential as predictor variables in region- or basin-specific model development.

Furthermore, nonlinear effects need to be carefully considered, and the uncertainties at high intensities of shaking that dominate seismic hazard are a key outstanding question before their use can be considered in future NSHMs.

We also observe that these challenges in capturing localized site effects are not unique to Wellington. The degree of systematic residual site amplification effects observed in Wellington is relatively common in other basin locations in New Zealand. Furthermore, basins with strong impedance contrasts (including shallow basins) are also not uncommon; the Wellington basin is a prominent and well-studied example.

It is also worth emphasizing that for more general applications in the NSHM, improved site characterization of national network stations is a priority. Particularly, the improved characterization of V_{S30} and other basin depth parameters (e.g., T_0, $Z_{1.0}$, $Z_{2.5}$, etc.) that together describe the full soil profile down to rock depths. The current uncertainties in these potential predictor variables limit the robust exploration of region-specific and/or partially nonergodic modeling approaches.

DATA AND RESOURCES

All data and resources are cited in relevant locations in this article. A series of underpinning technical reports provide more detail on specific datasets, processing, and interpretations; many of these are available with the release of the New Zealand National Seismic Hazard Model (NZ NSHM) 2022 at https://nshm.gns.cri.nz/Resources/ScienceReports (last accessed August 2023). A Wellington V_{S30} database was developed as part of this study and is shown in Figure 5; this is a collation of individual measurements from disparate studies, including some unpublished studies and confidential commercial reports. The majority of this database can be made available on request. The unpublished manuscripts by C. A. de la Torre, B. A. Bradley, R. L. Lee, A. Tiwari, L. Wotherspoon, J. Ridden, A. Kaiser (2024), "Analysis of site-response residuals from empirical ground-motion models to account for observed sedimentary basin effects in Wellington, New Zealand"; and by R. Lee, B. Bradley, M.

Hill, C. de la Torre, A. Kaiser, and L. Wotherspoon (2024), "3D ground motion simulation-based site amplification considering multiple basin geometries: A Wellington, New Zealand, case study," both submitted to *Earthquake Spectra*.

DECLARATION OF COMPETING INTERESTS

The authors acknowledge that there are no conflicts of interest recorded.

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REFERENCES

Abrahamson, N., W. Silva, and R. Kamai (2014). Summary of the ASK14 ground-motion relation for active crustal regions, *Earthq. Spectra* **30,** no. 3, 1025–1055, doi: 10.1193/070913EQS198M.

Al Atik, L. A., N. Abrahamson, J. J. Bommer, F. Scherbaum, F. Cotton, and N. Kuehn (2010). The variability of ground-motion prediction models and its components, *Seismol. Res. Lett.* **81,** no. 5, 794–801, doi: 10.1785/gssrl.81.5.794.

Ameri, G., F. Hollender, V. Perron, and C. Martin (2017). Site-specific partially nonergodic PSHA for a hard-rock critical site in southern France: adjustment of ground motion prediction equations and sensitivity analysis, *Bull. Earthquake. Eng.* **15,** 4089–4111, doi: 10.1007/s10518-017-0118-6.

Atkinson, G. M. (2023a). Evaluation of Wellington basin site amplifications based on ground motion modeling, *GNS Science Rept. 2023/46*, GNS Science, Lower Hutt, New Zealand, 30 pp., doi: 10.21420/JEC8-X984.

Atkinson, G. (2023b). Backbone ground motion models for crustal, interface, and slab earthquakes in new zealand from equivalent point source concepts *Bull. Seismol. Soc. Am.* doi: 10.1785/0120230144.

Atkinson, G., and J. Adams (2013). Ground motion prediction equations for application to the 2015 national seismic hazard maps of Canada, *Can. J. Civil Eng.* **40,** 988–998.

Atkinson, G., and D. Boore (2003). Empirical ground-motion relations for subduction zone earthquakes and their application to Cascadia and other regions, *Bull. Seism. Soc. Am.* **93,** 1703–1729.

Atkinson, G. M. (2022). Backbone ground-motion models for crustal, interface and slab earthquakes in New Zealand. Lower Hutt (NZ), *GNS Science Rept. 2022/11*, 61 pp., doi: 10.21420/QMJ6-P189.

Baltay, A. S., T. C. Hanks, and N. A. Abrahamson (2017). Uncertainty, variability, and earthquake physics in ground-motion prediction equations, *Bull. Seismol. Soc. Am.* **107,** no. 4, 1754–1772.

Barker, P. R., W. R. Stephenson, N. D. Perrin, and Z. R. Bruce (2016). It's our fault: Using microtremors (SPAC measurements) to assess various geotechnical parameters at 25 sites in the greater Wellington region, *GNS Science Rept. 2012/176*, **xi,** 131 pp.

Boore, D., J. Stewart, E. Seyhan, and G. Atkinson (2014). NGA-West2 equations for predicting PGA, PGV, and 5% damped PSA for shallow crustal earthquakes, *Earthq. Spectra* **30,** 1057–1085.

Bora, S., B. Bradley, E. Manea, M. Gerstenberger, R. Lee, P. J. Stafford, G. Atkinson, A. Kaiser, C. DiCaprio, and R. Van Dissen (2024). Hazard sensitivities associated with ground-motion characterization modeling for the new zealand national seismic hazard model revision 2022, *Bull. Seismol. Soc. Am.* doi: 10.1785/0120230167.

Borcherdt, R. D. (1970). Effects of local geology on ground motion near San Francisco Bay, *Bull. Seismol. Soc. Am.* **60,** 29–61.

Bozorgnia, Y., N. A. Abrahamson, S. K. Ahdi, T. D. Ancheta, L. Al Atik, R. J. Archuleta, G. M. Atkinson, D. M. Boore, K. W. Campbell, B. S.-J. Chiou, *et al.* (2022). NGA-Subduction research program, *Earthq. Spectra* **38,** no. 2, 783–798, doi: 10.1177/87552930211056081.

Bozorgnia, Y., N. A. Abrahamson, L. A. Atik, T. D. Ancheta, G. M. Atkinson, J. W. Baker, A. Baltay, D. M. Boore, K. W. Campbell, B. S.-J. Chiou, *et al.* (2014). NGA-West2 research project, *Earthq. Spectra* **30,** no. 3, 973–987, doi: 10.1193/072113EQS209M.

Bradley, B., S. Bora, R. Lee, E. Manea, M. Gerstenberger, P. Stafford, G. Atkinson, G. Weatherill, J. Hutchinson, C. de la Torre, *et al.* (2024). Summary of the ground motion characterisation model for the 2022 New Zealand National Seismic Hazard Model, *Bull. Seismol. Soc. Am.*, in review.

Bradley, B. A. (2013). A New Zealand-specific pseudospectral acceleration ground-motion prediction equation for active shallow crustal earthquakes based on foreign models, *Bull. Seismol. Soc. Am.* **103,** no. 3, 1801–1822, doi: 10.1785/0120120021.

Bradley, B. A. (2015). Systematic ground motion observations in the Canterbury earthquakes and region-specific non-ergodic empirical ground motion modeling, *Earthq. Spectra* **31,** no. 3, 1735–1761, doi: 10.1193/053013eqs137m.

Bradley, B. A., L. M. Wotherspoon, A. E. Kaiser, B. R. Cox, and S. Jeong (2018). Influence of site effects on observed ground motions in the Wellington region from the M_W 7.8 Kaikōura, New Zealand, earthquake, *Bull. Seismol. Soc. Am.* **108,** no. 3B, 1722–1735, doi: 10.1785/0120170286.

Çağnan, Z., and S. Akkar (2019). Assessment of aleatory and epistemic uncertainty for ground-motion intensity measure prediction in Turkey assessment of aleatory and epistemic uncertainty for GMIM prediction in Turkey, *Bull. Seismol. Soc. Am.* **109,** no. 1, 263–283.

Campbell, K. W., and Y. Bozorgnia (2014). NGA-West2 ground motion model for the average horizontal components of PGA, PGV, and 5%

damped linear acceleration response spectra, *Earthq. Spectra* **30,** no. 3, 1087–1115, doi: 10.1193/062913EQS175M.
Chiou, B. S. J., and R. R. Youngs (2014). Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra, *Earthq. Spectra* **30,** no. 3, 1117–1153, doi: 10.1193/072813EQS219M.
Cubrinovski, M., J. D. Bray, C. de la Torre, M. J. Olsen, B. A. Bradley, G. Chiaro, E. Stocks, L. Wotherspoon, and T. Krall (2018). Liquefaction-Induced Damage and CPT Characterization of the Reclamation at CentrePort Wellington, *Bull. Seismol. Soc. Am.* **108,** no. 3B, 1695–1708.
de la Torre, C. A., B. A. Bradley, F. Kuncar, R. L. Lee, L. M. Wotherspoon, and A. E. Kaiser (2022). Combining observed linear basin amplification factors with 1D nonlinear site-response analyses to predict site response for strong ground motions: Application to Wellington, NZ. Lower Hutt (NZ), *GNS Science Rept. 2022/37*, GNS Science, Lower Hutt (NZ), doi: 10.21420/0XB3-0266.
de la Torre, C. A., B. A. Bradley, F. Kuncar, R. L. Lee, L. Wotherspoon, and A. E. Kaiser (2023). Combining observed linear basin amplification factors with 1D nonlinear site-response analyses to predict site response for strong ground-motions: Application to Wellington, New Zealand, *Earthq. Spectra* doi: 10.1177/87552930231209726.
Foster, K. M., B. A. Bradley, C. R. McGann, and L. M. Wotherspoon (2019). A V_{s30} map for NZ based on geologic and terrain proxy variables and field measurements, *Earthq. Spectra* **35,** no. 4, 1865–1897.
Gerstenberger, M., S. Bora, B. Bradley, C. DiCaprio, R. Van Dissen, G. Atkinson, C. Chamberlin, A. Christophersen, K. Clark, G. Coffey, *et al.* (2022). New Zealand National Seismic Hazard Model 2022 revision: model, hazard and process overview, *GNS Science report; 2022/57*, GNS Science, Lower Hutt (NZ), doi: 10.21420/TB83-7X19.
Gerstenberger, M., S. Bora, B. Bradley, C. DiCaprio, R. Van Dissen, G. Atkinson, C. Chamberlin, A. Christophersen, K. Clark, G. Coffey, *et al.* (2024). The 2022 New Zealand National Seismic Hazard Model: Process, overview and results, *Bull. Seismol. Soc. Am.* doi: 10.1785/0120230182.
Hassani, B., and G. M. Atkinson (2017a). Site-effects model for central and eastern North America based on peak frequency and average shear-wave velocity, *Bull. Seismol. Soc. Am.* **108,** no. 1, 338–350, doi: 10.1785/0120170061.
Hassani, B., and G. M. Atkinson (2017b). Application of a site-effects model based on peak frequency and average shear-wave velocity to California, *Bull. Seismol. Soc. Am.* **108,** no. 1, 351–357, doi: 10.1785/0120170062.
Heron, D. W. (2020). *Geological Map of NZ 1:250 000. GNS Science Geological Map 1* (Third Ed.), Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand.
Hill, M. P., A. E. Kaiser, L. M. Wotherspoon, and E. F. Manea (2023). Using 3D geological models to create maps of estimated V_{s30} and site period, in *NZSEE 2023 Annual Conf.*, Auckland, New Zealand, New Zealand Society for Earthquake Engineering, 6 pp.
Hill, M. P., A. E. Kaiser, L. M. Wotherspoon, E. F. Manea, R. L. Lee, C. A. de la Torre, and B. A. Bradley (2022). 3D geological modelling of Wellington, *GNS Science Rept. 2022/23*, doi: 10.21420 TS0B-8A37.
Holden, C., A. E. Kaiser, R. J. Van Dissen, and R. Jury (2013). Sources, ground motion and structural response characteristics in Wellington of the 2013 Cook Strait earthquakes, *Bull. N. Z. Soc. Earthq. Eng.* **46,** no. 4, 188–195.
Hutchinson, J., B. A. Bradley, R. Lee, L. Wotherspoon, M. Dupuis, C. Schill, J. Motha, A. E. Kaiser, and E. Manea (2022). *2021 New Zealand Ground-Motion Database*, *GNS Science Rept. 2021/56*, GNS Science, Lower Hutt, New Zealand, doi: 10.21420/Z20E-5507.
Hutchinson, J., C. Zhu, B. Bradley, R. Lee, L. Wotherspoon, M. Dupuis, C. Schill, J. Motha, E. Manea, and A. Kaiser (2023). 2023 New Zealand ground motion database, *Bull. Seismol. Soc. Am.*, doi: 10.1785/0120230184.
Kaiser, A., N. Balfour, B. Fry, C. Holden, N. Litchfield, M. Gerstenberger, E. D'Anastasio, N. Horspool, G. McVerry, J. Ristau, *et al.* (2017). The 2016 Kaikōura, New Zealand, earthquake: Preliminary seismological report, *Seismol. Res. Lett.* **88,** no. 3, 727–739.
Kaiser, A. E., M. P. Hill, L. M. Wotherspoon, S. Bourguignon, Z. R. Bruce, R. Morgenstern, and S. Giallini (2019). Updated 3D basin model and NZS1170.5 subsoil class and site period maps for the Wellington CBD: Project 2017-GNS-03-NHRP, *GNS Science Consultancy Rept. 2019/01*, 63 pp.
Kaiser, A. E., E. F. Manea, L. M. Wotherspoon, M. P. Hill, R. L. Lee, C. A. de la Torre, A. C. Stolte, S. S. Bora, B. A. Bradley, A. Hulsey, *et al.* (2022). Revision of the National Seismic Hazard Model for New Zealand: Overview of site/basin effects, including a case study of the Wellington basin, *GNS Science Rept. 525 2022/56*, 46 pp., doi: 10.21420/3XXY-T303.
Kaiser, A. E., C. Van Houtte, N. D. Perrin, L. Wotherspoon, and G. H. McVerry (2017). Site characterisation of GeoNet stations for the NZ strong motion database, *Bull. N. Z. Soc. Earthq. Eng.* **50,** no. 1, 39–49.
Kamai, R., N. A. Abrahamson, and W. J. Siva (2016). V_{s30} in the NGA GMPEs: Regional differences and suggested practices, *Earthq. Spectra* **32,** no. 4, 2083–2108.
Kotha, S. R., M. D. Bindi, and F. Cotton (2017). From ergodic to region- and site-specific probabilistic seismic hazard assessment: Method development and application at European and Middle Eastern sites, *Earthq. Spectra*, **33,** no. 4, 1433–1453 .
Lee, R. L., B. A. Bradley, F. C. Ghisetti, and E. M. Thomson (2018) Development of a 3D velocity model of the Canterbury, NZ, region for broadband ground-motion simulation, *Bull. Seismol. Soc. Am.* **108,** no. 4, 2130–2147.
Lee, R. L., B. A. Bradley, M. Hill, C. A. de la Torre, A. E. Kaiser, and L. M. Wotherspoon (2022). 3D ground motion simulation-based site amplification considering multiple basin geometries: A Wellington, NZ, case study, *GNS Science Rept. 2022/40*, 51 pp., doi: 10.21420/R21F-3C28.
Lee, R., B. Bradley, E. Manea, J. Hutchinson, and S. S. Bora (2023). Evaluation of empirical ground-motion models for the 2022 New Zealand National Seismic Hazard Model revision, *Bull. Seismol. Soc. Am.* doi: 10.1785/0120230180.
Manea, E. M., A. E. Kaiser, M. Hill, L. Wotherspoon, S. Bourguignon, S. Bora, and A. Stolte (2024). A high-resolution site amplification map for Wellington, capital of New Zealand, *Seismol. Res. Lett.* doi: 10.1785/0220230227.
McVerry, G. H., J. X. Zhao, N. A. Abrahamson, and P. G. Somerville (2006). NZ acceleration response spectrum attenuation relations for crustal and subduction zone earthquakes, *Bull. N. Z. Soc. Earthq. Eng.* **39,** no. 1, 1–58, doi: 10.5459/bnzsee.39.1.1-58.
Perrin, N. D., D. W. Heron, A. E. Kaiser, and C. Van Houtte (2015). V_{s30} and NZS 1170.5 site class maps of NZ, Paper Number O-07, in

New Dimensions in Earthquake Resilience: 2015 NZ Society for Earthquake Engineering Technical Conf. and AGM, 10–12 April 2015, Energy Events Centre, Rotorua, NZ Society for Earthquake Engineering.

Perron, V., C. Gélis, B. Froment, F. Hollender, P. Y. Bard, G. Cultrera, and E. M. Cushing (2018). Can broad-band earthquake site responses be predicted by the ambient noise spectral ratio? Insight from observations at two sedimentary basins, *Geophys. J. Int.* **215,** no. 2, 1442–1454.

Petersen, M. D., A. M. Shumway, P. M. Powers, C. S. Mueller, M. P. Moschetti, A. D. Frankel, S. Rezaeian, D. E. McNamara, N. Luco, O. S. Boyd *et al.* (2020). The 2018 update of the US National Seismic Hazard Model: Overview of model and implications, *Earthq. Spectra* **36,** no. 1, 5–41.

Seebeck, H., R. J. Van Dissen, N. J. Litchfield, P. M. Barnes, A. Nicol, R. M. Langridge, D. J. A. Barrell, P. Villamor, S. M. Ellis, M. S. Rattenbury, *et al.* (2023). The New Zealand Community Fault Model - version 1.0: An improved geological foundation for seismic hazard modeling, *N. Z. J. Geol. Geophys.* doi: 10.1080/00288306.2023.2181362.

Semmens, S., G. D. Dellow, and N. D. Perrin (2010). It's our fault - Geological and geotechnical characterization of the Wellington central business district, *GNS Science Consultancy Rept. 2010/176*, 52 pp.

Seyhan, E., and J. P. Stewart (2014). Semi-empirical nonlinear site amplification from NGA-West2 data and simulations, *Earthq. Spectra* **30,** no. 3, 1241–1256, doi: 10.1193/063013eqs181m.

Shumway, A. M., M. D. Petersen, P. M. Powers, S. Rezaeian, K. S. Rukstales, and B. S. Clayton (2020). The 2018 update of the US National Seismic Hazard Model: Additional period and site class data, *Earthq. Spectra* 8755293020970979, doi: 10.1177/8755293020970979.

Stafford, P. J. (2022). A model for the distribution of response spectral ordinates from New Zealand crustal earthquakes based upon adjustments to the Chiou and Youngs (2014) response spectral model, *GNS Science Rept. 2022/15*, doi: 10.21420/5098-0S19.

Standards New Zleand (2004). Structural design actions - Part 5: Earthquake actions – NZ, NZ Standard NZS 1170.5:2004.

Stirling, M. W., G. H. McVerry, and R. K. Berryman (2002). A New Seismic Hazard Model for NZ, *Bull. Seismol. Soc. Am.* **92,** no. 5, 1878–1903, doi: 10.1785/0120010156.

Stirling, M. W., G. H. McVerry, M. C. Gerstenberger, N. J. Litchfield, R. J. Van Dissen, K. R. Berryman, P. Barnes, L. M. Wallace, P. Villamor, R. M. Langridge, *et al.* (2012). National seismic hazard model for NZ: 2010 update, *Bull. Seismol. Soc. Am.* **102,** no. 4, 1514–1542, doi: 10.1785/0120110170.

Stolte, A., L. Wotherspoon, B. Cox, C. Wood, S. Jeong, and J. Munro (2023). The influence of multiple impedance contrasts on mHVSR site period estimates in the Canterbury Plains of New Zealand and implications for site classification, *Earthq. Spectra* **39,** no. 1, 288–309, doi: 10.1177/87552930221130762.

Stronach, A., and T. Stern (2021). A new basin depth map of the fault-bound Wellington CBD based on residual gravity anomalies, *N. Z. J. Geol. Geophys.* 1–15, doi: 10.1080/00288306.2021.2000438.

Thomson, E. A., B. A. Bradley, and R. L. Lee (2020) Methodology and computational implementation of a NZ Velocity Model (NZVM2.0) for broadband ground motion simulation, *N. Z. J. Geol. Geophys.* **63,** no. 1, 110–127, doi: 10.1080/00288306.2019.1636830.

Vantassel, J., B. R. Cox, L. M. Wotherspoon, and A. Stolte (2018). Mapping depth to bedrock, shear stiffness, and fundamental site period at CentrePort, Wellington, using surface-wave methods: Implications for local seismic site amplification, *Bull. Seismol. Soc. Am.* **108,** no. 3B, 1709–1721, doi: 10.1785/0120170287.

Wotherspoon, L., C. Hayden, A. Stolte, B. Bradley, R. Lee, S. Jeong, and A. Kaiser (2020). 'Rapid' geophysical characterisation of New Zealand sedimentary basins using the horizontal-to-vertical spectral ratio method, *Earthquake Commission Rept. 18/761*, Paper Number 2351, available at https://www.eqc.govt.nz/assets/Publications-Resources/Funded-Research-papers/2351-Horizontal-to-vertical-spectral-ratio-methodWotherspoon.pdf (last accessed September 2022).

Wotherspoon, L. M., A. E. Kaiser, E. Manea, and A. C. Stolte (2022). Site characterisation database summary report, *GNS Science Rept. 2022/28*, doi: 10.21420/363X-CK83.

Wotherspoon, L. M., A. E. Kaiser, A. Stolte, and E. F. Manea (2024). Development of the Site Characterization Database for the 2022 New Zealand National Seismic Hazard Model, *Seismol. Res. Lett.* doi: 10.1785/0220230219.

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