

Article

Changes in Tsunami Risk to Residential Buildings at Omaha Beach, New Zealand

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Received: 29 January 2019; Accepted: 26 February 2019; Published: 2 March 2019



Abstract: Coastal settlements worldwide have suffered significant damage and loss to tsunami hazards in the last few decades. This period coincides with socio-economic changes that have heightened spatio-temporal risk through increased coastal development and infrastructure. In this study, we apply a spatio-temporal loss model to quantify the changes in direct economic losses to residential buildings from tsunami hazards over a 20-year period in Omaha Beach, New Zealand. The approach reconstructed temporal urban settlement patterns (1992, 1996, 2006 and 2012) for an area potentially exposed to regional source tsunami inundation hazard. Synthetic depth–damage functions for specific building classes were applied to estimate temporal damage and loss from tsunami inundation exposure at each building location. Temporal loss estimates were reported for a range of risk metrics, including probable maximum loss, loss exceedance and average annual loss. The results showed that an increase in the number of buildings and changes to building design (i.e., storeys, floor area, foundations) influenced the increasing risk to direct economic loss over the study period. These increases were driven by conversion from rural to urban land use since 1996. The spatio-temporal method presented in this study can be adapted to analyse changing risk patterns and trends for coastal settlements to inform future tsunami mitigation measures and manage direct economic losses.

Keywords: tsunami hazard; coastal development; building attributes; synthetic vulnerability functions; direct economic losses; spatio-temporal risk changes

1. Introduction

Tsunamis have caused frequent loss of life and damage to buildings and infrastructure along exposed and vulnerable coastlines in the last few decades. Rapid population growth, driven by increasing social and economic demand to live, work and holiday in coastal areas, has intensified building and infrastructure development in these locations [1,2]. Consequently, development intensification has exacerbated population and financial exposure to coastal flood hazards, including tsunami. Indeed, the 2004 Indian Ocean Tsunami (IOT) and the 2011 Great East Japan Earthquake and Tsunami (GEJET) demonstrate the catastrophic potential for economic loss and loss of life when coastal settlements are exposed to tsunami [3].

Risk analysis informs disaster risk managers of the potential consequences from future natural hazard events, providing a basis for making risk-informed decisions regarding land-use development [4]. Risk is often expressed in disaster management as the potential physical, absolute or relative socio-economic losses for single or multiple event scenarios over a specified time period [5,6].

Tsunami risk analysis involves an understanding of the tsunami hazard in any given coastal location as well as its vulnerability, which is underpinned by historical and future changes in development and population characteristics of that location.

Loss models are used in tsunami risk analysis to evaluate the potential consequences of different scenarios by relating hazard intensities (e.g., flow depth and/or velocity) with the vulnerability of exposed elements (e.g., buildings, people, infrastructure) [7–10]. Vulnerability functions, which describe the relationships between hazard intensity and asset damage response, are used in the modelling process to estimate economic losses. These are developed as either damage or fragility curves. Damage curves represent the building damage response as a ratio or percentage of the economic cost of replacement to restore the building to its pre-damaged condition [11]. In contrast, fragility curves describe the conditional probability that a damage state will be reached or exceeded for a given hazard intensity [12]. Both are further classified as (1) empirical, which are functions derived from damage surveys or insurance claim datasets or (2) synthetic, which are based on either laboratory tests or expert knowledge on the damage response to hazard intensity. In the absence of empirically based vulnerability functions for use in loss estimation, context-specific synthetic curves are typically developed, for example, in [13,14].

The risk to elements exposed to a given hazard is often expressed as the temporal recurrence or annual probability of loss. However, this risk is not static in time; it can change due to changes in the hazard (e.g., sea level rise exacerbating tsunami hazard or mitigation measures) or changes to the exposed elements (e.g., new building developments and construction design). Identifying changes to the assets at risk and their vulnerability to the hazard over a given timeframe provides insight on dynamic exposure, vulnerability and how risk evolves [15]. Risk estimation of direct economic losses is widely practiced in tsunami risk analysis [4,7–10,16–18]. However, economic loss scenarios often limit risk estimation to a single point in time. This is usually determined by the availability of physical and/or numerical tsunami inundation scenarios and spatial inventories of elements at risk for a given location, including the availability of context-specific vulnerability information. This limits risk analysis from informing decision-makers on how the risk has changed over time, including the cost-effectiveness of risk reduction and/or mitigation activities to minimize future losses from tsunami hazards. Understanding how elements at risk from tsunamis have changed can support forecasting of trends that inform decision-making on activities to reduce losses in future events. Furthermore, information from such analyses provides a tool for planners and decision-makers to develop cost-benefit models for regulatory or non-regulatory tsunami risk management operations.

The objective of this study was to quantify and assess the changes in direct economic loss to buildings over a 20-year period from tsunami hazards at a local scale and in a location with limited empirical tsunami impact and vulnerability data. The influence of sea level rise on tsunami hazard was not considered in this study due to only 3 cm (1.5 ± 0.1 mm/year) of mean sea level rise in this region over the study period [19]. A spatio-temporal methodology was applied at Omaha Beach, New Zealand, to identify building density and attributes in 1992, 1996, 2006 and 2012 exposed to tsunami hazards (Figure 1). Context-specific synthetic damage curves were developed and applied in scenario-based loss models to estimate changes in direct economic losses for buildings exposed to tsunami hazards over this period. The drivers influencing the observed changes, including wider implications and limitations of this study, are discussed within the context of dynamic building exposure and evolving tsunami risk.

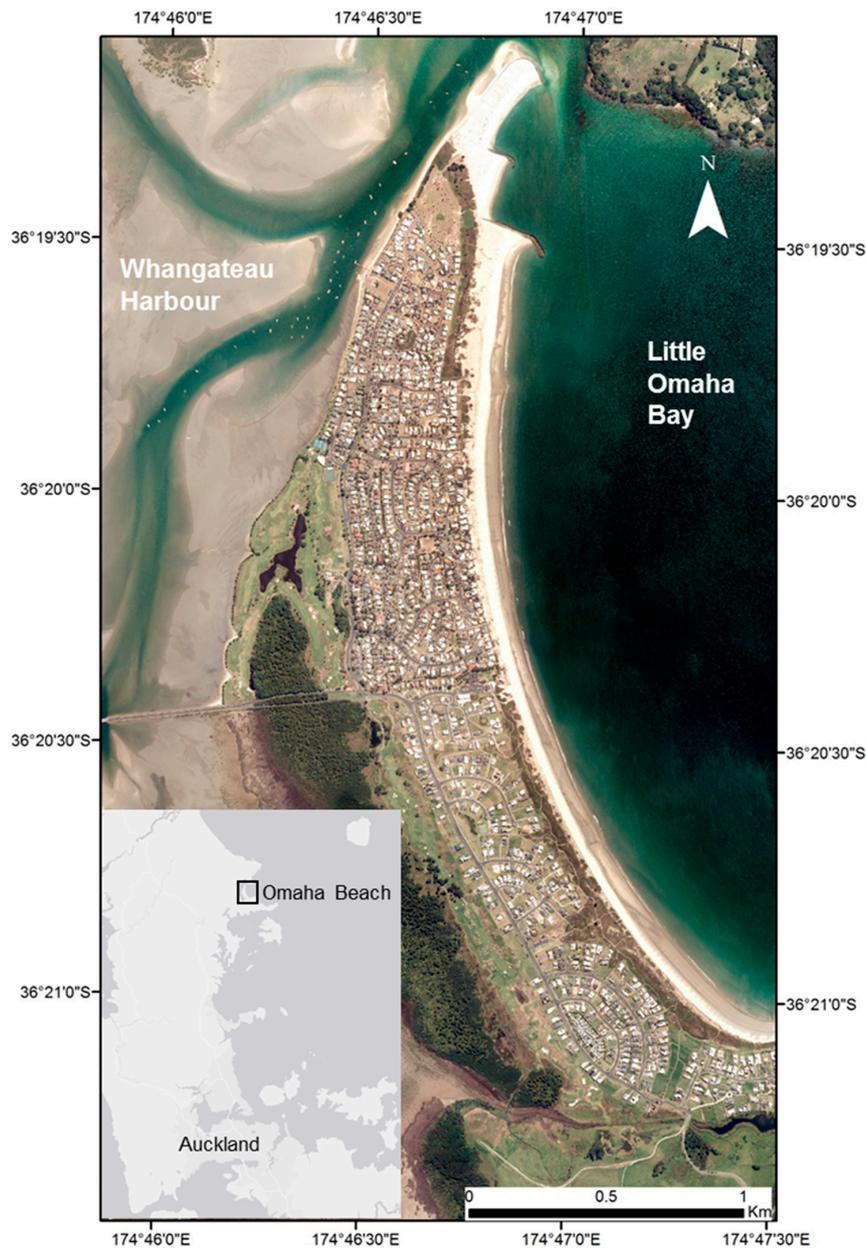


Figure 1. Overview of study location and urban settlement at Omaha Beach in 2012.

2. Materials and Methods

Tsunami loss scenarios were used to assess the spatial and temporal risk variations at Omaha Beach, with risk described as the direct economic loss to buildings for the selected years 1992, 1996, 2006 and 2012. The study was restricted to these years due to available aerial photography for Omaha Beach. The methodology used to estimate risk is described in seven sections: (1) description of study area; (2) loss modelling framework and application tool; (3) tsunami hazard data used in the analysis; (4) spatial building inventories for each study year; (5) synthetic vulnerability (damage) function development; (6) risk estimation of direct losses to buildings; and (7) limitations in estimating direct economic losses.

2.1. Study Area

Omaha Beach is a coastal suburb located 74 km north of Auckland, New Zealand (Figure 1). The urban settlement is located on a fine-grain Holocene barrier sandspit, which separates Whangateau

Harbour from Little Omaha Bay [20]. In the 20th century, the sandspit was used for pastoral production (e.g., sheep and beef farming), with residential building development occurring on the central spit in the 1960s. A mix of temporal and permanent residential building development steadily occurred until 2001, when a residential subdivision of over 700 parcels transformed the southern and northern sandspit from pastoral and scrub land to urban residential settlement. In 2006, Omaha Beach had a permanent residential population of 417, which can increase up to six times during the summer holiday period [21].

Omaha's location on the northeast New Zealand coast exposes it to a range of coastal inundation hazards, including local, regional and distant source tsunamis. Indeed, geological evidence for a potential 14th century event has been reported at Omaha Beach [22]. More recently, a maximum peak-to-trough height of ~2.5 m was observed for the 1960 Chile tsunami in Leigh Harbour, 6km north of Omaha Beach. [23]. No observed run-up or building damage was reported at Omaha Beach, though the sandspit was still largely used for pastoral production. However, numerical modelling for a range of tsunami scenarios suggests the possibility of severe inundation at Omaha Beach [24], indicating there is a significant tsunami hazard in this rapidly developing area.

2.2. Loss Modelling

Loss modelling was performed using RiskScape software (Version 0.2.84). RiskScape is an open-access software application built on a generic loss model framework that relates spatial information about natural hazard intensity (e.g. tsunami) and assets at risk (e.g., buildings) to vulnerability functions that estimate direct and indirect economic loss [25]. The software is configured for multiple hazard, asset, vulnerability and loss types, including tsunami. The system's modularity supports interchangeable spatial layers, which allows for estimating the direct economic loss to buildings for each tsunami scenario in each study year. The loss model inputs used in this study are described in Sections 2.3–2.5

2.3. Tsunami Hazard

The regional source tsunami inundation scenarios modelled in [24] for Omaha Beach provided the underpinning hazard data used in this study. Whilst Omaha Beach is potentially exposed to local, regional and distant source tsunami hazards [22,23], regional source tsunamis pose the greatest inundation threat to buildings in the area. The Kermadec Trench subduction zone was identified as the most likely source for regional tsunamis impacting Omaha Beach in [26,27]. Uncertainty in the seismic parameters was systematised using a logic tree. The Kermadec Trench was broken into unit sources (100 km by 50 km patches), and offshore tsunamis were calculated based on 1 m slip for each source. An arbitrary offshore tsunami time series was then rapidly calculated, assuming linear superposition following [26]. A Monte Carlo method assuming a truncated Gutenberg–Richter relationship with a 'b' value of 1 was then used to calculate 100,000-year synthetic time series for each branch of the logic tree. Based on offshore Auckland wave height, the logic tree branch for the 84th percentile (mean plus one standard deviation) was selected, and the 100 largest tsunamis from that were selected for inundation modelling. See [28] for further details on the selection of events. The hydrodynamic River and Coastal Ocean Model (RiCOM) [29–33] was then used to model the inundation of these 100 'worst' events, assuming bare-earth LiDAR topography gridded into a digital elevation model (DEM) at a spatial resolution of 10 m [24]. Maximum inundation depths, which provide the hazard intensity used in this study, were calculated on land for each of these 'worst' 100 events, and the results were represented as digital raster (.asc) layers (Figure 2). These layers for each tsunami scenario were intersected with building feature locations in each study year to extract the intensity measure for vulnerability function estimation of direct economic loss.

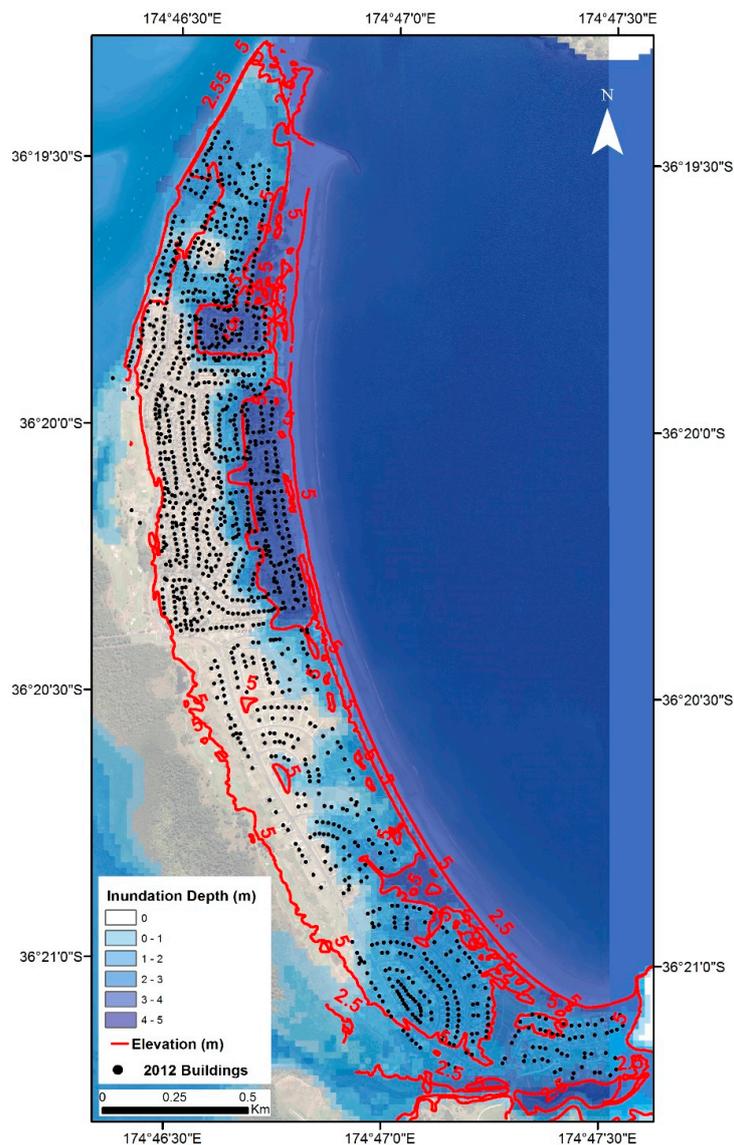


Figure 2. Modelled maximum tsunami inundation extent at Omaha Beach.

2.4. Buildings at Risk

The features of buildings at Omaha Beach were obtained from a spatial building inventory developed for New Zealand [34,35]. The inventory provides georeferenced feature locations for 2012 buildings, along with structural and non-structural attributes. Aerial photography captured in 2012 was used to visually validate building locations using ArcGIS10.1, and approximately 10% of building locations were corrected. In addition, a random sample of 300 buildings (~25%) was observed on Google Street view to assess the accuracy of building construction frame and storey attributes. Construction frame and storey attributes were updated for 5% and 2% of these buildings, respectively.

Aerial imagery for Omaha Beach was also acquired for 1992, 1996 and 2006. Temporal building feature datasets representing 1992, 1996 and 2006 were created by (1) removing all features with 'year of construction' values that correspond or post-date the aerial image year; (2) visually checking aerial imagery for the feature's presence; (3) digitising 'missing' features; and (4) applying 'averaged' or 'proportionate' attribute values to missing temporal building features (Table 1). Attributes applicable for building replacement cost estimation and vulnerability function application in the loss model were either retained or assigned to each temporal building feature. Importantly, aerial imagery post-2012 was not available for Omaha Beach, thereby restricting this study to the period 1992–2012.

Building replacement costs were estimated from 2012 construction industry valuation guidelines [36]. Replacement cost rates (\$/m²) were assigned to each building feature based on construction frame, storeys, foundation type and floor area. The applicable rate was multiplied by floor area to estimate the total replacement cost. Replacement costs for 1992, 1996 and 2006 building features were adjusted for inflation based on New Zealand's capital goods price index [37]. The index provides temporal capital asset cost changes for residential and non-residential building constructions. This informed replacement cost inflation adjustments for 1992 (−93.5%), 1996 (−70.4%) and 2006 (−26.6%) buildings relative to 2012.

Table 1. Statistics relating to building attribute for the Omaha Beach urban settlement in each study year.

Building Attributes		Year				
		1992	1996	2006	2012	
Buildings	Count	568	669	1096	1303	
	Missing	43	30	54	58	
Use Category	Residential	448	557	956	1147	
	Non-Residential	120	112	140	156	
Construction Frame	Timber	Count	557	658	1068	1270
		%	98.1	98.4	97.4	97.5
	Concrete Masonry	Count	11	11	28	33
		%	1.9	1.6	2.6	2.5
Storeys	1	Count	380	432	609	677
		%	66.9	64.6	55.6	52
	2	Count	173	219	451	587
		%	30.5	32.7	41.1	45
	3	Count	15	18	36	39
		%	2.6	2.7	3.3	3
Floor Area (m ²)	Mean	120	132	155	168	
	SD	71	74	85	91	
Floor Height (m)	Mean	0.49	0.52	0.42	0.4	
	SD	0.21	0.22	0.2	0.2	
Foundation	Piles	Count	436	493	737	812
		%	76.8	73.7	67.2	62.3
	Slab	Count	132	176	359	491
		%	23.2	26.3	32.8	37.7
Replacement Cost (\$NZD)	Sum	68,245,310	115,458,809	330,457,661	509,361,845	
	Mean	120,150	172,584	301,512	390,914	
	SD	93,999	122,573	203,527	256,619	

2.5. Vulnerability Functions

Damage curves estimate the economic loss value of a single building for a given hazard intensity [38]. This approach enables comparative building damage estimates from multiple tsunami inundation scenarios. Few building damage curves have been developed for tsunamis [39,40], and an absence of local empirical damage data meant 'synthetic' damage curves were developed for buildings at Omaha Beach.

Synthetic damage curve development requires three steps: (1) classify buildings based on construction frame material and number of storeys; (2) estimate the structure, external finishes, internal finishes and services component construction cost ratios (i.e., component construction cost/total

construction cost) for each building class; and (3) estimate component damage ratios based on material susceptibility to damage and replacement in response to increasing tsunami inundation depths. Six building classes were identified at Omaha Beach. Building class component cost ratios and 2012 replacement cost rates were estimated from construction industry valuation guidelines [36] and are presented in Table 2.

Table 2. Building class replacement costs, component cost ratios and synthetic tsunami depth–damage functions applied in this study.

Building Class	Replacement Cost (NZD 2012\$/m ²)	Component Cost Ratio				Synthetic Depth–Damage Function	R ²
		Structure	External Finishes	Internal Finishes	Services		
Timber—1 Storey	1850	0.19	0.31	0.39	0.11	$DR_B = -0.0329 \times D_{Flr}^2 + 0.3761 \times D_{Flr}$	0.99
Timber—2 Storey	2050	0.17	0.30	0.41	0.12	$DR_B = -0.0129 \times D_{Flr}^2 + 0.214 \times D_{Flr}$	0.98
Timber—3 Storey	3900	0.16	0.25	0.33	0.25	$DR_B = -0.0111 \times D_{Flr}^2 + 0.1829 \times D_{Flr}$	0.96
Concrete Masonry—1 Storey	1850	0.19	0.31	0.39	0.11	$DR_B = -0.0396 \times D_{Flr}^2 + 0.3638 \times D_{Flr}$	0.97
Concrete Masonry—2 Storey	2050	0.17	0.30	0.41	0.12	$DR_B = -0.0103 \times D_{Flr}^2 + 0.1712 \times D_{Flr}$	0.96
Concrete Masonry—3 Storey	3900	0.16	0.25	0.33	0.25	$DR_B = -0.0083 \times D_{Flr}^2 + 0.1372 \times D_{Flr}$	0.96

DR_B: building damage ratio; D_{Flr}: inundation depth above first finished floor level.

Component damage ratios are derived from estimates of material damage response to tsunami inundation depth above the first finished floor level. Internal finishes, services and some external finishes (e.g., doors, windows) require replacement upon water contact. Distribution of these components across multiple finished building levels reduces their overall damage susceptibility [41]. Structures and durable external finishes (e.g., concrete masonry wall cladding, roof cladding) are less susceptible to water-contact damage, with damage occurring at higher inundation depths when hydrodynamic forces may exceed building demand strength [4].

Damage curves estimate total component damage ratios (i.e., repair cost/replacement cost) at increasing inundation depth intervals until either a maximum component damage ratio or a complete building replacement is reached. For each building class, total component damage ratios were summed at intervals of 0.5 m depth, then 2nd order polynomial functions (Table 2) were heuristically fitted to produce simple continuous damage curves (Figure 3). The polynomial functions interpolate component damage ratios between depth intervals, representing a general trend of building damage in response to increasing inundation depth. Depth (D_{Flr}) was measured from the first finished floor level up (the damage ratio (DR_B) was assumed to be zero below this level). Damage curves were applied when depths above ground exceeded a building's first finished floor level ($DR = 0$) until a depth corresponding with expected maximum damage ($DR = 1$) or complete building replacement was reached. Once the tsunami depth above floor, D_{Flr} , reached 3 m, complete destruction was assumed for both the one-storey building classes, and the damage ratio was set to 1.

In general, concrete masonry building classes are assumed to have a lower damage susceptibility compared with their timber counterparts. Complete replacement damage states (i.e., damage ratios >0.85) for these building constructions correspond well with published fragility curve mean inundation depth estimates for similar timber [42–45] and concrete masonry building classes [40,45,46].

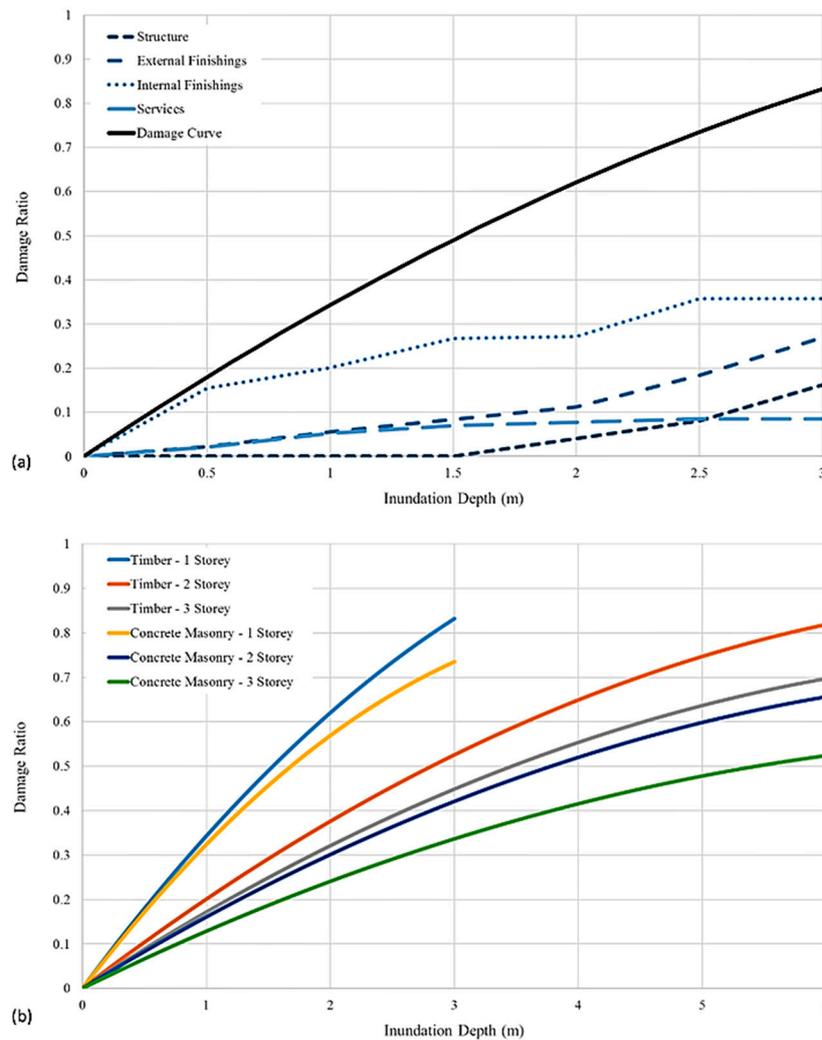


Figure 3. (a) ‘Timber—1 Storey’ building class component damage ratios with simplified ‘fitted’ synthetic depth–damage curve. (b) Synthetic depth–damage curves representing mean expected damage ratios for timber and concrete masonry building classes at Omaha Beach, New Zealand.

2.6. Risk Estimation

In this study, risk is defined as a conditional relationship between hazard intensity and vulnerability of elements at risk. Risk ($R_{ie|t}$) is conceptually described in [47] as follows:

$$R_{ie|t} = f(H_i, V_e)|_t \tag{1}$$

where losses for the element at risk (e.g., people, buildings, infrastructure) can be expressed as a vulnerability function, V_e , dependent on the hazard reaching or exceeding a given intensity at the element at risk location, H_i , and attributes of the risk element, e , characterising its ability to resist damage from exposure to the hazard intensity. $R_{ie|t}$ is the risk of loss sustained by an element sustaining loss due to a hazard event reaching or exceeding a given intensity over the time period, t .

Risk of direct economic loss to buildings at Omaha Beach from the modelled regional source tsunami hazard scenarios was calculated using the following equation in [47]:

$$v(p) = \sum_{i=1}^{NEvents} \Pr(P > p|Event i) F_A(Event i) \tag{2}$$

where $v(p)$ is the exceedance rate of loss, p ; $F_A(Event_i)$ is the $Event_i$ annual frequency of occurrence; and $\Pr(P > p | Event_i)$ is the probability of loss being greater than or equal to p , conditioned by the occurrence of the $Event_i$. The equation describes the loss exceedance (LE), a metric relating the expected loss for each annual return interval (ARI) (alternately, the annual rate for each loss to be reached or exceeded). Probable maximum loss (PML) is estimated from the maximum loss for a specified return interval. In addition, average annual loss (AAL) is obtained from a weighted average of all possible loss values, p . The AAL is calculated from the integral of $v(p)$:

$$AAL = \int_0^{\infty} v(p) dp \quad (3)$$

The AAL and LE were estimated for specified return intervals within the modelled regional source tsunami hazard scenario during the 100,000-year time series for Omaha Beach. PML is reported as the maximum tsunami inundation scenario loss estimate and is the highest loss exceedance (LE).

2.7. Limitations in Estimating Direct Economic Losses

In addition to the limitations in modelling the tsunami hazard provided in [24,28], the methodology to estimate temporal changes in economic loss has inherent limitations. Assumptions were made to identify assets at risk and transition through intervals between study years. Most building features were derived from a spatial inventory with accurate year of construction attributes [34,35]. Aerial photography resolution supported validation of building features. Digitising missing features can lead to overestimates of habitable floor areas and replacement costs as roof eaves and parapets can protrude beyond external walls by up to one metre. New Zealand residential buildings are required to have eave-overhangs from external walls between 0.45 and 0.75 m [48]. An average overhang of 0.6 m was assumed for missing features. Overhang areas were calculated from external length and then subtracted from digitised floor area.

Building replacement costs were estimated for each building class using construction industry valuation guidelines [49]. The industry guidance provides cost rates ($\$/m^2$) for generalised building types, corresponding to the building classes in Table 2. Individual buildings rates can vary considerably within these classes depending on building design specifications. Industry guidance suggests the average rates could differ up to 4 to 5 times between low and high specification buildings [36]. Replacement costs assigned to each building class were therefore assumed as average values.

3. Results and Interpretation

Results and interpretations are presented in three sections: (1) spatial distribution and building development patterns in each study year; (2) changes in tsunami exposure for each study year; (3) detailed descriptions and analysis of direct losses to buildings.

3.1. Building Development

The distribution of buildings at Omaha Beach in 1992, 1996, 2006 and 2012 are illustrated in Figure 4a–d. Total building numbers increased from 568 to 1303 over the study period. The average annual construction rate was 39 buildings/year, with rates per year doubling from 25 building/year between 1992 and 1996 to 52 buildings/year between 2006 and 2012. Over this period, residential buildings experienced a considerably higher total construction increase (256%) than non-residential buildings (31%). Rapid building development after 1996 is demonstrated in Figure 4b–d, following pastoral and scrub land subdivision for urban land use north and south of the pre-1996 urban area.

Residential building attributes changed as new construction proliferated the area after 1996. Average building size expanded, as indicated by increases in ‘floor area’ and multi-storey buildings (Table 1). Multi-storey (>1) building construction increased by 300% over the study period and, by 2012, formed a higher proportion of new residential buildings than single-storey construction. Similarly, mean floor area increased by 23%. After 1996, mean floor area for new building constructions was

202 m² (c.f., 132 m² for the existent building stock), increasing to 241 m² in 2012 (c.f., 168m² for the existing building stock). Floor areas for pre-1992 buildings were on average 40% smaller than new buildings constructed after 2006. Foundation type and floor height changes indicate the design of larger residential buildings with concrete slab foundations becoming prevalent. This foundation type increased between 1992 and 2012 by 337% for new building constructions. After 1996, concrete slabs occurred in just under 50% of buildings, corresponding with a mean floor height reduction of 0.12 m for all buildings at Omaha Beach. During this period, mean floor heights for concrete slab and pile foundations were 0.22 m (SD 0.09 m) and 0.6 m (SD 0.14 m).

Total building replacement costs for all buildings in the study area rose from NZD\$68.2 M in 1992 to NZD\$509.3 M in 2012. Land subdivision within and immediately north of the urban area in 1992 encouraged new residential building development. This growth added NZD\$11.7 M of total building replacement cost annually, reaching NZD\$115.4 M in 1996. Over the next 10 years, new building construction worth NZD\$214.9 M occurred on pastoral and scrub land beyond the 1996 urban area. A further NZD\$178.9 M worth of buildings were constructed after 2006. Peak building construction during this period contributed nearly NZD\$30 M in total replacement cost annually. Residential buildings accounted for 98% of total replacement costs for all buildings constructed since 1992.

3.2. Exposure of Buildings to Tsunami Hazards

Tsunami inundation scenarios were used to identify changes to a range of hazard exposure metrics for the study years, including inundation frequency and inundation depth. The spatial distribution of buildings constructed since 1992 showed an increase in building numbers exposed to tsunami inundation (Figure 4b–d). Within the modelled maximum tsunami inundation extent, 281 buildings were identified in 1992, including 219 residential. Building construction on land exposed to this inundation scenario increased by 28 per year on average between 1992 and 2012. By 2012, 841 buildings (750 residential) were exposed to inundation (Table 3). The highest construction rates observed on inundated land were between 1996 and 2006, reaching 35 buildings per year. During this period, rural-to-urban land conversion and residential building construction commenced.

Table 3. Summary of building inundation for all 100 modelled tsunami inundation scenarios.

Year	Inundation Metric	Building Inundation Descriptive Statistics				
		Max.	Min.	Mean	Median	SD
1992	Inundation frequency (all buildings)	281	1	149	182	97
	Inundation frequency (individual buildings)	100	1	53	62	24
	Inundation depth (metres above ground)	5.99	0.18	1.73	1.71	1.10
1996	Inundation frequency (all buildings)	357	3	203	254	128
	Inundation frequency (individual buildings)	100	1	56	69	23
	Inundation depth (metres above ground)	5.99	0.19	1.79	1.86	1.05
2006	Inundation frequency (all buildings)	707	8	340	363	239
	Inundation frequency (individual buildings)	100	1	48	50	24
	Inundation depth (metres above ground)	5.99	0.18	1.45	1.50	0.89
2012	Inundation frequency (all buildings)	831	9	344	398	276
	Inundation frequency (individual buildings)	100	1	46	47	24
	Inundation depth (metres above ground)	5.99	0.18	1.40	1.45	0.88

Although total inundation frequency for all exposed buildings increased during the study period, the inundation frequency of individual buildings decreased after 1996 (Table 3). In 1996, the mean inundation frequency for exposed buildings was 56 times out of 100 modelled scenarios. Inundation

frequency decreased to 48 times in 2006 and further to 46 times in 2012. This suggests that, on average, the new buildings constructed since 1996 had a lower inundation frequency than the existing buildings. This occurrence is notwithstanding an additional 474 new buildings developed on land within the modelled maximum inundation extent.

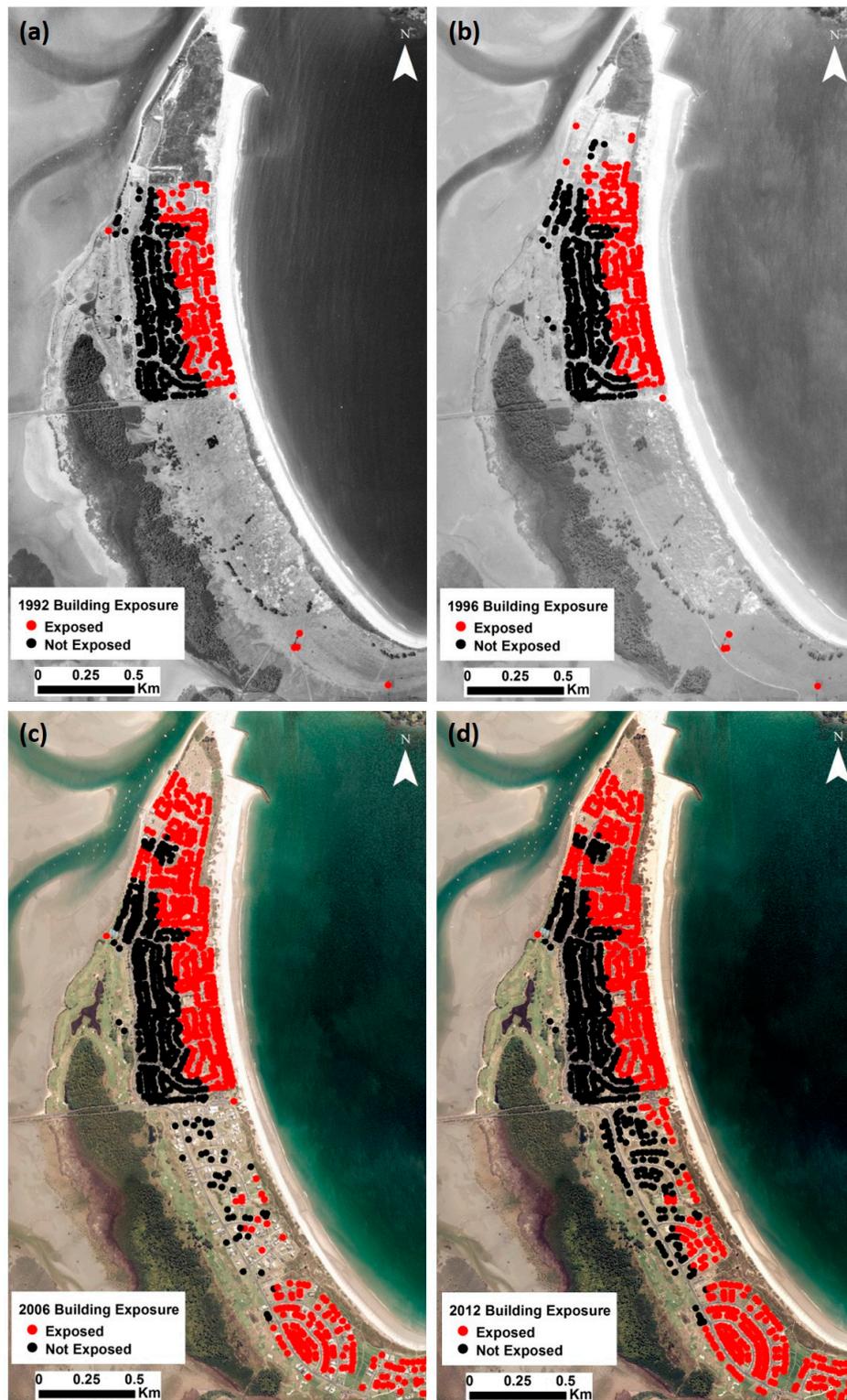


Figure 4. Urban settlement development in Omaha Beach in (a) 1992, (b) 1996, (c) 2006 and (d) 2012. Buildings exposed to modelled maximum regional source tsunami inundation are identified (red).

On average, inundation depths decreased for individual buildings after 1996. The mean inundation depths for individual buildings was 1.79 for all modelled tsunami scenarios in 1996, with over half exceeding 1.86 (Table 3). New building constructions after 1996 corresponded to a mean inundation depth reduction to 1.45 m in 2006 and a further 1.4 m by 2012. In 2012, approximately 420 buildings were exposed to inundation depths exceeding 1.4 m, which was over 300 more than in 1992.

3.3. Temporal Changes in Direct Economic Loss

The loss model results showed a considerable increase in direct economic loss between 1992 and 2012 (Table 4). Importantly, the results demonstrated increasing potential loss with building expansion at Omaha Beach over this period. The probable maximum loss represents the highest direct economic loss expected over a given time period. This was calculated for a range of time periods and for each study year. PML was estimated to increase from NZD\$22.9 M in 1992 to NZD\$193.9 M in 2012 (Table 4), i.e., an increase of +846%. On average, PML increased annually by NZD\$8.5 M over the 20-year study period. Although PML rose year upon year, variations in average annual rates were observed between construction periods. Lowest average annual PML rates of NZD\$5 M/year were observed between 1992 and 1996. Rapid building construction during the 1996 to 2006 period added NZD\$101.7 M to overall PML at a rate of NZD\$10 M/year. After 2006, this rate reduced slightly to NZD\$8.2 M per year over six years to 2012, i.e., an additional NZD\$49.2 M. Mean PML for all tsunami hazard scenarios was NZD\$81,602 in 1992, increasing to NZD\$120,352 in 1996, NZD\$204,664 in 2006 and NZD\$233,380 in 2012. These results demonstrate a maximum direct economic loss increase for individual buildings of almost three times over the 20-year study period.

Table 4. Estimated building loss exceedance (LE) and average annual loss (AAL) for each study year in \$NZD. Probable maximum loss (PML) is the equivalent of the 100,00-year LE value.

ARI	1992		1996		2006		2012	
	LE	AAL	LE	AAL	LE	AAL	LE	AAL
100,000	22,930,041	9262	42,965,498	18,188	144,697,181	51,034	193,938,461	64,544
50,000	21,315,706	9040	40,176,812	17,772	136,281,684	49,631	180,478,055	62,676
20,000	20,495,108	8410	38,665,837	16,585	129,105,059	45,679	169,861,649	57,451
10,000	18,751,854	7423	36,369,891	14,701	115,386,284	39,548	151,007,601	49,419
5000	17,383,859	5616	33,715,826	11,193	103,798,281	28,686	134,108,116	35,345
2500	12,143,002	2584	24,300,622	5241	59,836,295	11,618	75,042,091	13,865
1000	0	0	0	0	0	0	0	0

Loss exceedance (LE) provides a probability or likelihood of direct economic loss being reached or exceeded for each tsunami inundation scenario. Across all inundation scenarios, mean LE increased by +760% between 1992 and 2012, from NZD\$9.3 M to NZD\$64.1 M. The likelihood of mean LE estimates in each study year corresponded to 2000–2200 year ARI. Relative to 1992, mean LE increased 96% by 1996, a further 444% by 2006 and a further 220% by 2012. Median LE corresponded to a 2000 ARI. A minor difference was observed between the mean and median LE estimates for 1992 and 1996 (\pm NZD\$1.4 M), although the mean LE was NZD\$5.9 M to NZD\$10 M higher for 2006 and 2012, respectively. No losses were observed in any year for the 1000-year ARI despite the inundation exposure of only nine buildings in 2012.

Estimates of tsunami loss exceedance at a building scale were higher for buildings constructed after 1992. Mean LE over all damaged buildings increased by NZD\$71,968 (260%) between 1992 and 2012. This estimate rose to \$119,218 (364%) during this period when only considering new buildings. The highest increases in annual mean LE rate of new buildings (NZD\$6,439) were observed between 2006 and 2012, corresponding with mean LE estimates per building rising from NZD\$125,952 to NZD\$164,595. Relative to 1992, a considerable increase in mean building PML (i.e., maximum LE) occurred in the construction period 2006–2012, reaching NZD\$266,469 (+591%).

The average annual loss increased by 6.6 times on average between 1992 and 2012. Mean AAL for all years studied translated to a 2500–2700 year ARI, roughly 500 years higher than the LE estimates for the corresponding building years. The largest AAL increase rates occurred in the 1996 to 2006 period. The mean AAL increase over this period was NZD\$795, rising to NZD\$3,284 for the PML scenario. From 1992 to 1996, mean AAL for all scenarios was NZD\$653, slightly higher than the NZD\$503 between 2006 and 2012. Low AAL estimates relative to LE for individual inundation scenarios resulted from the 100,000-year regional tsunamigenic earthquake time series used to simulate tsunami inundation hazards.

4. Discussion

Urban settlement at Omaha Beach is distinguished by rapid residential building growth between 1992 and 2012. Reconstruction of settlement patterns identified building distribution and attribute changes over this period that increased potential direct economic loss in modelled regional source tsunami hazard scenarios. Rural-to-urban land-use conversion since 1996 promoted residential building construction on land at risk to tsunami inundation. Over 97% of construction frames for new buildings were timber, a framing material highly susceptible to tsunami damage, particularly when inundation depths exceed 2 m [42,43,45,46]. On average, the number of storeys and floor area size also increased during the study period as a consequence of a growing permanent and semi-permanent resident population, creating demand for larger buildings to support these living arrangements. Changing building attributes to support permanent occupation is indicated by increased multi-storey buildings (332%) and average floor area by 59 m² between 1996 and 2012. Omaha Beach resident population grew by almost 50% between 2006 and 2013 [19].

Modern residential building construction in New Zealand has observed an increase in concrete slab foundations [49]. At Omaha Beach, this trend was observed with a 337% increase in concrete slab foundations for buildings constructed after 1992 and just under 50% of new buildings between 2006 and 2012. The low floor heights above ground, typically 0.2 to 0.3m, increase damage potential for highly susceptible internal finishes and services. Despite a mean inundation depth decrease for exposed buildings from 1.73 m in 1992 to 1.4 m in 2012, concrete slab foundations offset potential inundation depth reduction and internal building damage at new residential building locations.

The urban settlement at Omaha Beach in 1992 had encroached onto coastal foredunes. Settlement expansion since 1996 has been predominantly located on land fronted by relatively intact foredunes. During the 2004 IOT, coastal barriers such as sand dunes were observed to offer land protection against tsunami inundation in Sri Lanka [50]. Fore-dune protection at Omaha Beach may have contributed to an observed decrease in mean building inundation depth and frequency for the exposed building distribution since 1996. New building developments after 1996 mostly occurred on land opposite foredunes and were both less frequently exposed to lower magnitude tsunami inundation events and affected by lower inundation depths in higher magnitude events. However, as tsunami inundation was not modelled using a representative high-resolution DEM for each study year, further detailed investigation is required at the study location to better understand the potential role of foredunes in reducing exposure and risk for new building developments. Although relative exposure to tsunami hazard metrics decreased at a building scale over the study period, risk metrics analysed to estimate direct economic loss, such as probable maximum loss and loss exceedance, all demonstrate a considerable increase of more than 300% in response to increasing number, size (i.e., number of storeys and floor area) and replacement values for new building developments on land exposed to tsunami.

The changing risk trends presented in this study can be observed in the context of recent coastal settlement development on coastlines vulnerable to tsunami hazards. Analysis of settlement growth and susceptibility to direct damage from tsunami inundation informs risk mapping and potential strategies to mitigate economic loss to current and future building developments. Land-use conversion from rural to urban in an area with high amenity values has an important influence on increased risk of direct economic loss from regional source tsunami hazards. However, the low likelihood of

tsunami hazard and loss recurrence may influence decision-makers in selecting appropriate mitigation strategies based on risk. Estimating risk using a range of metrics, including probable maximum loss, event loss exceedance and average annual loss, provides options to assess avoidance or the effectiveness of mitigation measures for different scenarios to a given annual return interval event. This enables land-use or emergency managers to identify coastal settlements where risk of direct economic loss has increased over time and assess community risk tolerance to help identify appropriate mitigation measures. The methods and information presented in this study informs cost–benefit analysis for community decisions on whether to ‘do nothing’ or manage future economic risk in tsunami hazard zones through mitigation measures, such as avoiding new building development, adopting more tsunami-resilient building designs or maintaining or enhancing the protective capability of coastal barriers.

In the present study, only direct economic loss for buildings exposed to regional source tsunami hazards were considered. Future studies could improve this information by including additional direct (e.g., residential building contents) or indirect (e.g., clean-up cost, temporary accommodation) economic losses for affected buildings and infrastructure. In addition, threat to human life should also be considered where urban settlement expansion on coastal land at risk to tsunami hazards results in temporal population changes. Extending tsunami hazard scenarios to include local and distant source tsunami would give a complete analysis of economic risk from the tsunami hazard.

This study only examined the change in risk that occurred over a 20-year period. However, the same methodology could be used in predictive models, where potential future settlements could be considered and their influence on the risk profile of the built environment assessed. In that way, planners could decide whether the increased risk due to increased building density or attributes was acceptable or whether such changes should be avoided due to an unacceptable increase in risk.

5. Conclusions

This study demonstrates changing risk of direct economic loss to buildings from tsunami hazard at Omaha Beach, New Zealand. Over a 20-year period between 1992 and 2012, probable maximum loss and mean loss exceedance for modelled regional source tsunami inundation scenarios increased by +846% and +760%, respectively. Reconstruction of urban settlement patterns indicates that risk increased in response to rapid residential building growth since 1996, following rural-to-urban land-use conversion. New urban land development exposed a higher number of buildings to tsunami hazard, while relatively larger residential building constructions increased the replacement value of assets at risk to tsunami damage. Although mean tsunami inundation depth and frequency over exposed buildings were observed to have decreased since 1996, this was only because more buildings are now exposed. Furthermore, the prevalence of concrete slab foundation use in new building designs has offset potential inundation depth reduction and internal building damage at new residential building locations.

The spatio-temporal method presented in this study to estimate the changing risk of direct economic loss to buildings is replicable for other coastal settlements. Mapping urban settlement patterns can be performed using GIS and aerial imagery to identify buildings at risk to tsunami hazards at different periods of time. In the absence of local empirical data, estimating direct building damage and loss for specific buildings at risk can create synthetic damage function information obtained from the knowledge of building component damage response to tsunami inundation. This approach enables a range of risk metrics to report direct economic loss to buildings, including probable maximum loss, event loss exceedance and average annual loss, for regional source tsunami inundation hazards. This information supports cost–benefit analysis and community decisions on implementing mitigation measures to manage future economic risk in tsunami hazard zones. While only direct economic loss to buildings was considered in this study, the methodology can be extended for a more comprehensive risk analysis, including a broader range of direct and indirect losses to buildings and infrastructure as well as the threat to human life. With risk information, planners can decide whether

a potential increase in economic or social risk with land-use changes is acceptable or whether the risk is unacceptable and should be avoided or mitigated.

Author Contributions: Conceptualization, R.P. and E.L.; Data curation, R.P., E.L. and W.P.; Formal analysis, R.P.; Funding acquisition, R.P.; Methodology, R.P. and S.W.; Project administration, R.P. and S.W.; Resources, R.P. and S.W.; Validation, E.L. and W.P.; Writing—original draft, R.P.; Writing—review & editing, E.L., S.W. and W.P.

Funding: This research was funded by NIWA Taihoro Nukurangi through the New Zealand Government's Science Strategic Investment Fund (SSIF), grant number CARW1802, and the APC was funded through grant number CARW1901.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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