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ENHANCING RESILIENCE BY ALTERING OUR APPROACH TO EARTHQUAKE AND FLOODING ASSESSMENT: MULTI-HAZARDS

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ABSTRACT

Natural hazard reviews reveal increases in disaster impacts nowhere more pronounced than in coastal settlements. Despite efforts to enhance hazard resilience, the common trend remains to keep producing disaster prone places. This paper explicitly explores hazard versus multi-hazard concepts to illustrate how different conceptualizations can enhance or reduce settlement resilience. Understandings gained were combined with on-the-ground lessons from earthquake and flooding experiences to develop of a novel 'first cut' approach for analyzing key multi-hazard interconnections, and to evaluate resilience enhancing opportunities.

Traditional disaster resilience efforts often consider different hazard types discretely. However, recent events in Christchurch, a New Zealand city that is part of the 100 Resilient Cities network, highlight the need to analyze the interrelated nature of different hazards, especially for enhancing lifelines system resilience. Our overview of the Christchurch case study demonstrates that seismic, hydrological, shallow-earth, and coastal hazards can be fundamentally interconnected, with catastrophic results where such interconnections go unrecognized.

In response, we have begun to develop a simple approach for use by different stakeholders to support resilience planning, pre and post disaster, by: drawing attention to natural and built environment multi-hazard links in general; illustrating a 'first cut' tool for uncovering earthquake-flooding multi-hazard links in particular; and providing a basis for reviewing resilience strategy effectiveness in multi-hazard prone environments. This framework has particular application to tectonically active areas exposed to climate-change issues.

Keywords: Resilience; Multi-hazards; Earthquake-flooding assessment framework; Post-Disaster Recovery; Canterbury Earthquake Sequence

1. INTRODUCTION

Reviews of natural hazards and disasters worldwide show an exponential rise in the impacts on people and economies over the last century, a rise that is recognized as out-of-step with changes in Earth system dynamics (Mileti 1999, Smith 2013, Blaikie et al. 2014, Montz et al. 2017). This rise has also reportedly been accompanied by a shift from earthquakes to flooding as the highest impacting disasters (UNISDR 2017). Populations and built environments are growing overall, and nowhere faster than in coastal settlements (Hallegatte et al. 2013, Nicholls and Cazenave 2010), with 23% of people residing in coastal areas at the turn of the century (Small and Nicholls, 2003), and 40% by 2016. Small coastal settlements, delta cities and coastal megacities alike face the challenges of living

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in environments characterized by natural and altered processes of coastal erosion and sediment budget dynamics; inundation under periodic extreme tides, storms, and/or inter-annual to inter-decadal ocean-atmosphere dynamics; pluvial and fluvial flooding; salinization, subsidence, relative rises in sea and groundwater levels; as well as accelerating absolute sea level rises and changes in storm and ocean conditions as a result of anthropogenic climate change (Pelling and Blackburn 2014). Around the Pacific and Indian Oceans, many coastal settlements face the added challenges of living with direct and/or cascading seismic hazards (Berz et al. 2001, Dilley 2005, Hart et al. 2015, Kamat 2015).

For each of the abovementioned environmental phenomena and processes, our sub-discipline specific knowledge, understanding, data records and prediction capabilities are ever improving with time and advances in measurement and modelling techniques in the geophysics, hydrology, seismic engineering and atmospheric sciences. Meanwhile several initiatives driven by collectives such as the Intergovernmental Panel on Climate Change (IPCC), the C40 Cities and its Connecting Delta Cities (CDC) network, and the 100 Resilient Cities organization have elevated the sharing and dissemination of best-practice adaptation and resilience enhancing approaches to a global scale. Urban resilience refers to "*the ability of an urban system and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity*" (Meerow et al. 2016, p39). But despite the best efforts of multiple fields of experts to enhance the resilience of human settlements to natural hazards, the commonly acknowledged trend has been the continued development and creation of disaster prone environments (Kamat 2015).

Over the last half century there has been an expanding discourse seeking to explain the ever-increasing impacts of natural hazards on human settlements. Explanations have emerged and evolved, including realizations of the limits of responses founded in 'nature control' paradigms, and of under-representation of human factors in our analyses of disasters, including culture, socio-economics, planning and politics, playing a central role in the vulnerability of coastal settlements (Adger et al. 2005). More recently, United Nations initiatives such as the Hyogo Framework for Action (2005-2015) and the Sendai Framework (2015-2030) have sought to coordinate communities of interest on a global scale and to reduce disasters by encouraging better data collection and use, common standards and targets, and legally-based instruments for disaster risk reduction.

This paper contributes to efforts to understand why impacts from natural hazards have been growing in coastal settlements worldwide by addressing how our framing of natural hazards in general, and of earthquake and flood hazards in particular, can directly affect our capacity to design, build and maintain resilient urban environments. Natural hazards associated with earthquake and flooding events are traditionally conceptualized distinctly, as 'geological' and 'hydrological' phenomenon. In response to lessons learned during recent disaster and recovery processes in New Zealand, we explore 'multi-hazard' concepts to illustrate how different ways of understanding hazards can either enhance or reduce settlement resilience. That is, we review literature on how differences can arise in how we approach earthquakes and flooding through 'hazard' versus 'multi-hazard' lenses. Next we use a simple multi-hazard lens to begin to develop a 'first-cut' method for analyzing the key interactions that exist between earthquakes and flooding, interactions that need to be accounted for to plan, design and manage resilient settlements and lifelines systems.

2. METHODOLOGY

Our approach to the challenge of understanding the roles of earthquakes and flooding in modern built environments, including lifelines systems, begins with a basic reframing of hazard conceptualizations and, thus, ways of identifying opportunities for building resilience. Through literature review, we critique traditional hazard (3.1.1) versus multi-hazard (3.1.2) ways of understanding human environments, and multi-hazard assessment framework (3.1.3), drawing out specific lessons that are pertinent to our earthquake-flooding case study. Then we review information on the case study: the Christchurch city experiences of the Canterbury Earthquake Sequence (CES) and post-earthquake flooding landscape (3.2.1). Finally we describe a simple, 'first cut' framework (3.2.3) for predicting and measuring multi-hazard connections between earthquake and flooding hazards, with a particular focus on those that can affect urban drainage system resilience. This framework is structured around 2 steps. Step 1 involves tabulating the main physical and built environment elements involved in each hazard phenomenon, then identifying those via which multi-hazard connections might exist. For our case study, the main categories of natural and built environment components that make up earthquakes and their associated hazards, and different types of flooding hazard were tabulated. Step 2 analyzed the nature of each potential multi-hazard interaction, categorizing interactions as those that might increase and/or decrease the intensity or effects of the primary hazard. All interaction timescales were included, such that a multi-hazard interaction may occur before, after or coincident with an event of the hazard under consideration. Our discussion explores the broad implications of each of the above identified multi-hazard interaction to reveal where potential resilience gains and losses might exist.

3. RESULTS

3.1 Literature Analysis

3.1.1 Tensions Arising With Traditional 'Hazard' Approaches

Not all hazards are interrelated and not all places are subject to multiple types of hazard within human timeframes. However, most natural hazards manifest as interactions between human systems, including built environments, and some combination of the geophysical, geomorphic, hydrological atmospheric, and/or biological processes operating in Earth's inherently interconnected system. These interconnections mean that few types of natural hazard operate independent of other hazards. This is especially true of natural hazards in coastal plain settlements, since coastal environments, by definition, are the interface between terrestrial and marine systems, places where a plethora of marine, coastal and terrestrial processes (and thus natural hazards) occur and interact.

Traditional strategies for building resilience to natural hazards and disasters have typically focused on discrete, supposedly disconnected hazard types. In such approaches, natural hazards are divided into process groups such as geophysical (e.g. earthquake, tsunami, volcanic eruption, landslide, snow avalanche), shallow earth (e.g. regional and local subsidence and uplift, erosion, mass movement), hydrological (e.g. flood, drought), atmospheric (e.g. extreme wind, hail, snow, lighting, thunderstorms, medium to longer term climate change), and biophysical (e.g. wildfire) (Gill and Malamud 2014). Natural hazard risk approaches commonly deal with just one of these hazards or hazard groups, including assessing the vulnerability of human use systems to that hazard or hazard group (Hart 2016).

As human knowledge and technical capabilities have grown over the last century, the study of specific natural hazards or hazard groups, including infrastructure design responses, have become increasingly specialized fields (Ger 2010). A quick web search reveals a situation where numerous professional societies, divisions within central and local governments, research institutes and international gatherings focus on advanced understandings of, and developments within the science of and engineering responses to individual hazard phenomena. Due to the high level of advancement, detailed knowledge and discipline specific modes of communication, the experience of engaging with any such science or engineering community by outsiders from 'different' specializations can range from enlightening to incomprehensible. Such advanced specialization can lead to the impression that '*we now understand much, and also know much about the gaps that need to be explored'* for each type of hazard, an impression that has oftentimes been (inaccurately) reinforced by media (Alexander 2014, and e.g. Time Magazine 2017, VOX Media 2017).

The above perception of 'advancement' is reinforced by the increasing sophistication of measurement technologies and analysis techniques, including statistical and geospatial. As an example of the former, an international shift is occurring in ways of assessing hazard event likelihood from the use of deterministic to probabilistic based statistical methods (e.g. UNISDR 2017, Todd et al. 2017), but the value of results produced from these techniques is underpinned by our basic ability to frame and gather useful information on the workings of each hazard or disaster phenomenon. As an example of the latter, geospatial advances in hazard science are epitomized by the New Zealand Geotechnical database (NZGD 2017), a data collection, storage and sharing platform that arose in response to the Canterbury Earthquake Sequence (CES), or by the level of citizen and official observations of the Great East Japan earthquake and tsunami events (e.g. Jung and Moro 2014, Kaku et al. 2015).

With such resources we are able to build sophisticated hazard models comprising GIS frameworks of the different above and below ground built environment and human factors, and the natural geomorphic and hydrological and geological environment layers that exist within the profile of an individual hazard system. These advanced models are good, but suffer from several issues which can help hide multi-hazard aspects: for example, the increasing specialization is commonly associated with increasing disciplinary siloization and, arguably, with a misperception of increased understanding. The hugely increased availability of data, sensing and response technologies in some countries is also not necessarily associated with safer urban environments. ‘Too much’, misapplication, or misinterpretation of technology can cause issues as demonstrated in the events surrounding the Tohoku tsunami in 2011. Public misinterpretation of the detailed information broadcast during this March 2011 event has led the Japanese government to simplify its warning scale while the Japanese National Broadcasting Agency, NHK, has also simplified the data provided during its broadcast tsunami warning alerts.

3.1.2 Multi-Hazard Approaches

Here we must address differences in what is meant by the terms ‘multi-hazard’ and ‘hazard’, and why these differences matter for those trying to understand, plan and build resilience to natural hazards into contemporary coastal and other settlements. Budimir et al. (2016) proposed a UNISDR definition of multi-hazard approaches as an “*approach that considers more than one hazard in a given place (ideally progressing to consider all known hazards) and the interrelations between these hazards, including their simultaneous or cumulative occurrence and their potential interactions*”

Often ‘hazard’ analyses identify two or more hazards operating in a particular area and/or overlay them via a geospatial system, where the hazards are co-located in space but essentially treated independently. The city of Kobe, Japan, for instance, provides an online hazard information platform with a webpage on each of the different river, overland and tsunami flooding phenomena, one page on landslides and debris-flow run-out potentials, and one on earthquakes (Kobe City 2017). In the ward of Nishinomiya, where several landslide run-out hazards exist that could cause river impoundments, this connection is not reflected in the potential flooding maps. In another example, Lamb (1997) reports on a hazard co-location study conducted for the city of Christchurch. This ‘multiple or many hazard’ report analyzed the various hazard risks facing the city’s lifelines systems, and was advanced for its time. In contrast, modern multi-hazard studies go beyond examining spatial co-location to identify the interrelations that exist, and interactions that might occur, between two or more hazards.

The idea of ‘multi-hazards’ begins with recognizing that many types of hazard are intricately linked as opposed to independent. We would also argue that, in contrast to some hazard research, the concept of multi-hazards conveys a situation where ‘*despite knowing some things, we have a limited idea of key gaps in our knowledge*’. As such, multi-hazard understandings suggest that single hazard approaches (including multiple hazard ones) can both under- and over-estimate risk, distort management priorities, and/or invoke responses to one hazard which increase vulnerability to another linked hazard (Hart et al. 2015, Budimir et al. 2016, Hart 2016, Hart and Hawke 2016, Todd et al. 2017). Multi-hazard approaches are more challenging due to their complexity and the early state of this research field, but they are also more promising in terms of likely opportunities to build resilience, since their ‘interrelated systems’ perspective better represents the natural, built and human environments of modern urban settlements (Gill and Malamud 2014, Hart et al. 2015, Budimir et al. 2016).

3.1.3 Multi-Hazard Assessment Methodologies

Multi-hazard assessment is not a new concept, though its track record of application is relatively nascent. Currently no standard international approach exists for multi-hazard investigations (e.g. compare Smith 2013, Kappes et al. 2012, Gill and Malamud 2014, and Liu et al. 2016). Most analyses are primarily based around a thematic or spatial framework. The simple framework for assessing multi-hazard interactions developed in this paper is largely thematic since it focuses on the intersection of earthquakes and flooding. While it is readily transferable to other locations, the broad procedure is also transferable to other multi-hazard combinations beyond the earthquake-flooding theme, since it is based on examining the commonalities and connections between the different 'layers' of multiple hazards in one environment.

Key terms used to frame the ways in which hazards interact include *spatial co-location*, *temporal coincidence* and *cascades*. Spatial co-location occurs when two or more hazard types affect the same location, regardless of the hazard frequencies or intervals between events. Temporal coincidence is the possibility that two or more types of hazard event can occur at the same time in the same place. Cascades refer to the occurrence of one hazard event, followed some time later by a second type of hazard occurrence, when the first event has altered some condition such that the second hazard is affected (e.g. second hazard triggered, or its effects exacerbated or lessened).

Relating these terms to our case study, the city of Christchurch has long been recognised as subject to the co-location of earthquake and flood hazards, amongst others (Lamb 1997). Changes in geomorphology, built environments and urban management systems after the CES affected the city's subsequent experiences of coastal, fluvial and pluvial flood hazards (i.e. cascading effects, see below and Allen et al. 2014 for details). The likelihood of future flooding has been irreversibly altered by CES events while the potential for future earthquake effects (such as those associated with liquefaction) could vary with any temporal coincidence of elevated groundwater levels, such as occur seasonally and during times of flood (Hart et al. 2015, Davis et al. 2015). The need to systematically capture and understand the details behind some of these interconnections was one of the key motivations behind the development of the framework described in this paper.

Another key aspect of multi-hazards of particular relevance to our earthquake-flooding themed study concerns engineering standards. When standards are designed for single hazards, they are vulnerable to undermining by multi-hazard interactions. The failure of the Tōhoku sea walls represents an example of this phenomenon. These coastal defence structures were designed to withstand waves exceeding the largest historically recorded tsunami and typhoon events along their coasts. In 2011 a larger tsunami event occurred, causing much wave-induced structural damage (Sato 2015). In addition to design event exceedance and direct tsunami damage, other contributing factors to wall failure included the subsidence and seismic motion-induced structural damage during the preceding earthquake. That is, when the waves arrived, some walls no longer met their original design standard. In localities that experienced smaller waves, sunken seawall crown armors and cracked revetments were observed in post-event surveys. In areas that experienced larger waves, many walls were badly damaged and/or swept hundreds of meters overland, such that damage caused by the preceding seismic event was likely masked and potentially underestimated (Kato et al. 2013).

Similar undermining of design standards has been observed in relation to stormwater and flood management systems in Christchurch city (Allen et al. 2014). The CES damaged numerous stop-bank structures, rendering them prone to failure in subsequent flood events. In another example, areas recognised as prone to flooding pre-CES were classified as 'flood management areas' in the district plan, and therein minimum floor levels were mandated to elevate dwellings above typical floodwater elevations. CES induced deformation and subsidence lowered ground surface and dwelling elevations across large parts of the city, including those characterised by shallow groundwater, meaning that the pre-quake standards for flood protection are no longer as effective.

Published multi-hazard assessments typically focus on cascading effects (Liu et al., 2016). Well-known examples include where earthquakes trigger tsunami, landslides or changes in relative sea levels, or where earthquake- or precipitation-induced landsides lead to the formation of unstable dams (e.g. Budimir et al. 2014, Hart et al. 2015). In their detailed and thoughtful review, Gill and Malamud

(2014) offer additional types of interconnection, such as where the probability of a second hazard is altered due to the occurrence of an initial hazard affecting an environmental threshold, or circumstances in which the risk and impacts from two or more hazards varies according to whether or not they occur together or separately in space or time on any occasion.

One of the difficulties in establishing a multi-hazard assessment approach is that methodologies vary greatly between different natural hazards, so that successfully integrating the analyses of multiple hazards can become a very complex task (e.g. Todd et al. 2017). Difficulties arise when comparing different types of hazard since they are characterized by different natures, intensities, return periods and effects on the environment as well as different intensity measurement methodologies, standards and reference units (Carpignano et al. 2009, Kappes et al. 2012). These issues can be partially, if not fully, addressed via the use of a standardizing classification technique (Menoni et al. 2006).

Gill and Malamud (2014) offer a useful example framework for multi-hazard analyses of natural hazards, based on four steps: namely (i) the identification and comparison of all relevant hazards; (ii) examination of all possible hazard interactions; (iii) investigation of the potential for temporal/ spatial hazard coincidences and (iv) examination of vulnerability dynamics, or how the multi-hazards might impact a community and their options for responding. Liu et al. (2016) outline a similar framework but with an additional stage where multiple hazards' probabilities and potential losses are brought together to assess multi-risks. Other researchers assessing multi-hazards and/or multi-risks employ matrices, vulnerability curves, probability or scenario trees, and/or risk maps (e.g. Carpignano et al. 2009). The present paper is limited to multi-hazard assessment. It should be noted, however, that assessing multi-risks in Christchurch forms part of ongoing research that the authors are involved in, concerned with implementing multi-hazard lessons at a local government level to reduce future disaster risks and build resilience in Christchurch city (e.g. Hart and Hawke 2016, Todd et al. 2017).

3.2 Case Study Analysis

3.2.1 Description of the Christchurch Context

The city of Christchurch is located between a large, braided Waimakariri River to the north and Banks Peninsula to the south. Most of the city occupies a broad, gently sloped, low-elevation coastal plain, the surface of which comprises the fringes of land built through Holocene shoreline progradation and fluvial aggradation. This city experienced a series of devastating earthquakes and aftershocks, beginning in September 2010, and known collectively as the Canterbury Earthquake Sequence (CES). From September 2010 to December 2011 alone, six earthquakes occurred with magnitudes between M_w 5.3 and 7.1, with Peak Ground Accelerations (PGAs) between 0.06 to 1.41 g and Peak Ground Velocities (PGVs) between 3.6 and 81.4 $cm.s^{-1}$ across the city and surrounding settlements (Bradley et al. 2014, pp 6-7). Ground deformation, settlement and subsidence during the CES (Quigley et al. 2013) produced relative sea level changes of comparable magnitudes to the climate-induced sea level rise predicted for the next century or more (Hart et al. 2015, Marsden et al. 2015).

In the years immediately following the CES start, certain Christchurch neighbourhood communities reported experiences of flooding hazards that they perceived as markedly altered compared to before the earthquakes. Community disquiet regarding the perceived changes in flooding hazards arose at a time when the city's drainage system was still in its initial repair stages. In response, central government and the Earthquake Recovery Minister were largely sceptical of the notion of post-quake enhanced flooding, querying whether or not flooding changes were due to permanent or temporary earthquake damages, or simply a result of climate dynamics. Then early 2014 a cluster of depressions occurred off the coast east of the city. Records show that similar storms commonly produce corresponding clusters of 3 to 4 severe flood events in Christchurch every decade or so (CCC 2014), although the first decade of the 2000s escaped such flooding due to a relatively dry period associated with a sustained negative phase of the Interdecadal Pacific Oscillation (IPO). The worst of these post-quake storms occurred in early March 2014, lasting several days with pressures as low as 992 hPa, and bringing >140 mm of rain in <40 hours to parts of the city, the heaviest sustained falls since the 1970s

(Allen et al. 2014). Simultaneously, local estuary and sea levels were elevated due to the occurrence of cyclical low-frequency high tides augmented by the storm surge produced by the low pressure system. Severe flooding ensued across coastal areas of the city as well as in some inland suburbs characterised by natural basins or topographic depressions.

Review and hydrological modelling studies after the March 2014 floods identified that, although Christchurch has long been susceptible to flooding under such meteorological conditions, certain CES factors had enhanced the city's fluvial, pluvial and coastal flooding hazards and contributed to the March 2014 experiences (Allen et al. 2014, CCC 2014, Hart et al. 2015, Hart and Hawke 2016, Todd et al. 2017). Key factors included changes in the city's geomorphology due to earthquake-induced land deformation and liquefaction, as well as post-earthquake construction activities creating watercourse and drainage system obstructions, plus disruption to the regular stormwater maintenance regime of things as simple as the autumn clearance of leaves and other debris from gutters and roadside sumps. In some areas flooding occurred mostly as a result of the earthquake impacts, while in other areas the earthquake effects served to increase inundation depths and extents for already flood-prone environments. Eventually public pressure plus findings from council and independent research studies, led to a change in the categories of earthquake damage recognised by the New Zealand government under the Earthquake Commission, the national insurance system for losses from natural hazards: the category "Increased Flooding Vulnerability" (IFV) was added. Moreover, the CES and post-quake flooding events produced an unprecedented opportunity for scientific, engineering and governance communities worldwide to deepen understanding of the multi-hazard interactions that can occur between earthquakes and various types of flooding in urban coastal settings. In this paper we use these understandings to underpin our multi-hazard assessment framework in order to predict and measure impacts and provide a decision support tool for building urban resilience.

3.2.2 A Initial Framework for Earthquake-Flooding Multi-Hazard Assessment

Here we outline a simple, novel approach to analyzing the key interconnections, cascades and feedbacks between 'earthquake' and 'flood' types of hazard in coastal city settings. Tables 1 and 2 illustrate our summary of natural and built environment components of earthquake and flooding phenomena, respectively (step 1). For earthquakes, we include associated cascading hazards such as liquefaction and tsunami, while for flooding we include elements related to fluvial, pluvial, groundwater and coastal types of flooding. The elements of each hazard type were categorized into those that could be altered by earthquake-flooding multi-hazard interactions (step 2). Tables 1 and 2 are to be read horizontally, with each row containing elements associated with the primary category in the first column, and being independent of any other row (i.e. no vertical order exists in the table beyond the header column). With the exception of tsunami, these earthquake and flooding hazard elements and multi-hazard effects were all observed in Christchurch during or after the CES and March 2014 flooding events (Figure 1).

This approach recognizes that, in a multi-hazard assessment context, it is not possible to provide a clear demarcation between hazards and vulnerabilities. The vulnerabilities of natural and built environment elements to one kind of hazard can, and should in fact, be regarded as hazardous elements for other phenomena. For example, the seismic vulnerability of a stormwater network, including the different levels and extents of damage sustained during an earthquake event, should be regarded as a key factor influencing flooding hazards. A first example of implementation of this concept is the work of Cavalieri et al. (2015, 2016), which investigates to what extent a storm might generate flooding should it occur in an area recently struck by a severe earthquake, where damaged stormwater and wastewater systems have not yet been fully repaired.

4. DISCUSSION

In her insightful paper, Kamat (2015, 529) states that "*the assessment of seismic and flood risk of urban areas depends mainly on the quality of the data available and the source of these datasets*". Based on our conceptual review, plus observations from the CES and subsequent flooding in

Table 1. Summary of natural and built environment elements that contribute to earthquake and their associated cascading hazards, including identification of elements which potentially affect or are affected by flooding (with respect to earthquake effects, *blue* indicates potential increases while *white* indicates no likely changes, in response to flooding multi-hazard interactions).

Faulting:	tectonic deformations	surface ruptures	tsunami intensity, reach & effects	topography & sediment deposit nature	
Seismic energy release:	peak ground velocities & accelerations	soil settlement and cyclic mobility	mass movement (erosion, landslides, rock falls)	liquefaction effects (lateral spreading, sediment/ water release	topography, soil structure, sediment deposition
Built environment:	building, bridge & port structural integrity & usability	dam & levee (stopbank) structural integrity	pipe & channel network structural integrity, capacity & functionality	surface material nature/ integrity (roads, swales, paving, parks)	electricity, gas, fuels telecom. network functioning

Table 2. Summary of natural and built environment elements of flooding hazards, including identification of elements which potentially affect or are affected by earthquakes (with respect to flooding effects, *blue* indicates potential increases while *green* indicates potential decreases &/ or increases, and *white* indicates no likely changes, in response to earthquake multi-hazard interactions). FMA = Flood Management Areas (in Christchurch these indicate exposure to '1 in 50' and '1 in 200' year floods).

Rainfall:	temporal variability & clustering	spatial variability	rainfall intensity	surface water runoff	surface infiltration
Land:	elevations above sea level & river banks	gradients, catchments, basins	surface cover, permeability, vegetation, roughness	geology, soil types, land mobility, erosion	FMA category & building floor level standards
Natural channels: (rivers, streams)	base flows & quick flows	channel capacities: cross-sections, sedimentation	channel bed profile, water surface profile	bank/ stopbank integrity & elevations	flood plain elevations, topography
Stormwater system built components:	soakage pits, detention basins, wetlands	grates, sumps, inlets, outlets, culverts, gates, bridges	road & swale secondary flow paths	pipe diameter, material, slope, depth	gravity & pump systems
Groundwater:	elevation above sea level	water table surface slope	depth below land surface	pressure	sea level responsive-ness
Ocean:	relative mean sea level	estuary capacity & tidal prism	extreme tides inundation zones	storm surge reach	potential tsunami inland reach

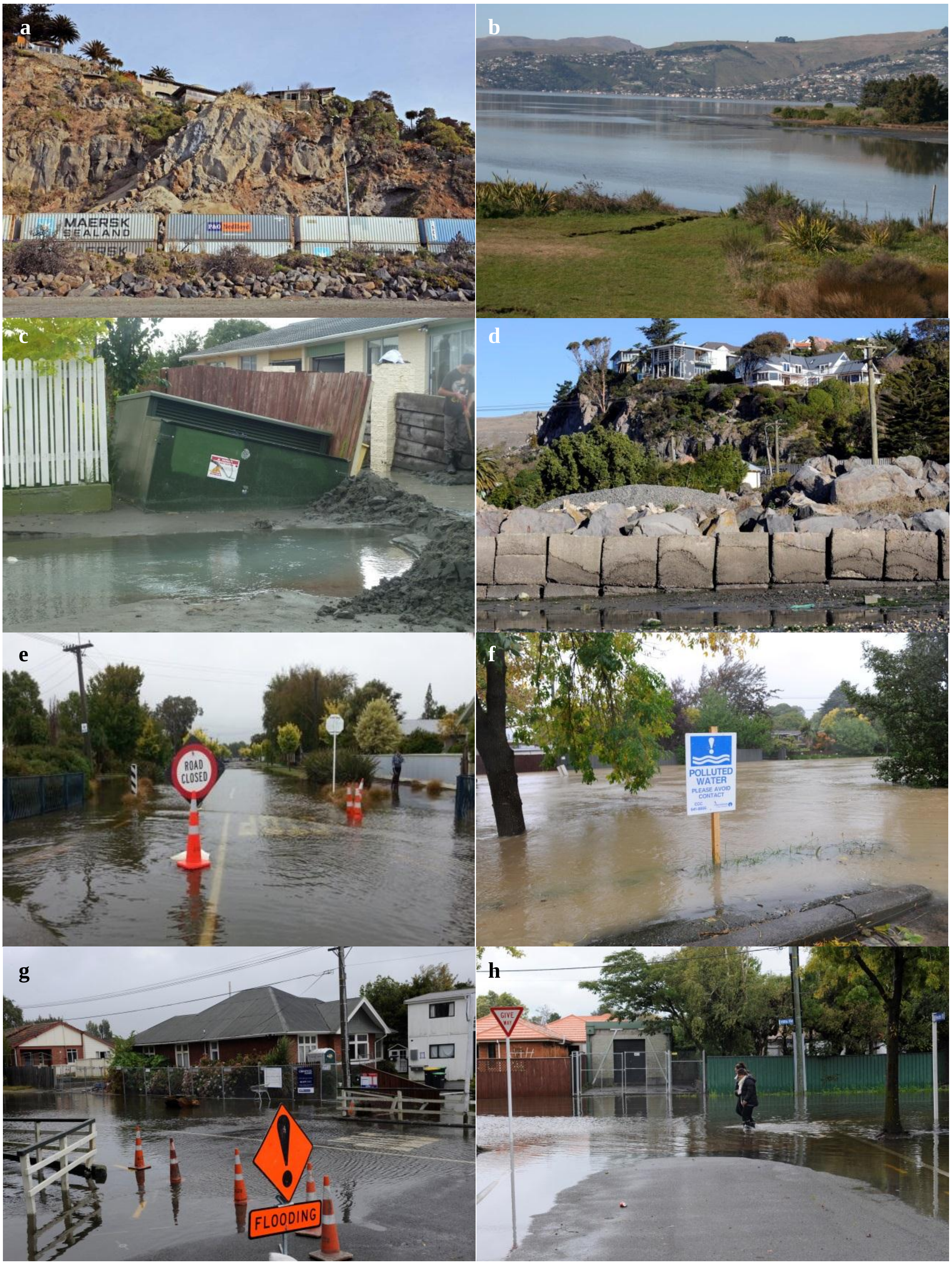

Figure 1. Multi-hazard interactions observed in Christchurch after the CES: (a) earthquake-induced rockfalls alongside the estuary threatened outlet dynamics and thus drainage, leading to significant post-quake flood prevention remediation works, (b) CES subsidence caused a 20% reduction in the estuary tidal prism thereby reducing drainage capacity during large flood events, (c) liquefaction induced flooding, (d) CES and post-quake response shoreline alterations affecting flood management, (e) a March 2014 flooded river-proximal road that had experienced subsidence during the CES, (f) road and swale flooding, with CES damage to gutter and sump structures visible in the foreground, (g) flooding in front of an earthquake damaged and waste-water disconnected brick dwelling in the background, and (h) flooding in front of an earthquake damaged electrical substation. Photo credits: Marney Brosnan and Su Young Ko.

Christchurch city, we would argue that the effectiveness of any such assessment is also strongly contingent on recognition and identification of the multi-hazard interrelations that might enhance, reduce or otherwise modify the potential effects of any natural hazard occurrences.

The Christchurch case study findings reinforce the non-discrete, highly-interconnected nature of so-called geological and hydrological hazard categories. Observations reveal how earthquake effects can significantly increase a city's susceptibility to several types of flooding, including via vertical tectonic movements, liquefaction induced settlement, and lateral spreading. Liquefaction and lateral spreading, in addition to sedimentation, may reduce river and estuary capacities (Hart et al. 2015). Earthquake effects can significantly affect overland and river channel flow, including damage to existing engineered flood protection and stormwater system components, and other key features involved in water storage and conveyance such as land surfaces, roads, swales, and soakage features. This has been an ongoing issue for lifelines systems in Christchurch, where multi-hazard interactions have undermined design standards and affected the functionality of the three waters and roading infrastructures for years post-quake (Allen et al. 2014, Filion and Sands 2016, Hart and Hawke 2016). Consequential risk changes included those in the likely future impacts of extreme weather events, coastal erosion and inundation, tsunami, groundwater rises, local and regional floods, and hill slope instability. Christchurch is now also beginning to recognize that the city's exposure to earthquake hazards has altered via hydrological feedback mechanisms such as the extension of liquefaction hazard zones due to reduced depths between subsided ground surfaces and groundwater tables.

The rebuild, recovery and regeneration phases in post-CES Christchurch demonstrate why the fundamental interconnections that exist between so-called 'seismic', 'hydrological', 'shallow earth', 'coastal' and other categories of natural and anthropogenic hazard need to be explicitly recognized and capitalized upon to enhance urban resilience (e.g. Allen et al. 2014, Hart et al. 2015, Hart 2016, Hart and Hawke 2016, Todd et al. 2017). In the initial stages of the rebuild, many of these interconnections went unrecognized. Notwithstanding the devastating effects on individuals and communities, one could argue that the city as a whole was somehow 'fortunate' to experience the 2014 cluster of extreme rainfalls and subsequent floods, amongst other smaller events, as a tangible demonstration of the effects of ignoring multi-hazard interactions, while still less than half-way though the engineered lifelines repair and recovery phase.

Recent international events indicate that multi-hazard environments are likely more typical than not for 21st century settlements, at least around the Pacific, as tragically epitomized by the 2011 Great Disaster of East Japan's seismic, tsunami and technological (nuclear) hazard events, and as evidenced in the 1999 Chi Chi Taiwan, 2008 Wenchuan China, and 2016 Kumamoto Japan earthquakes. With predicted changes in climate and ocean dynamics due to anthropogenic disruption, the exposure of many coastal cities and megacities to multi-hazard effects will likely increase if such effects continue to be under-recognized and underrated in planning, design and hazard mitigation practices.

Living through such an experience has increased recognition amongst Christchurch residents, and the New Zealand science, engineering, and government communities, of the realities of multi-hazard interactions and their role in potentially enhancing or creating disasters. For example, seismic damage and risk considerations alone initially led the Crown to purchase around 5400 households along the Avon River corridor so that buildings could be cleared and future earthquake risk reduced. But now plans exist to utilize the hydrology of this newly vacated floodplain and its linked river and wetland features to mitigate not only future earthquake risks but also the effects of ongoing and accelerating sea level rise and flooding hazards, while enhancing social, amenity, ecological and cultural values.

Christchurch applied to be a part of the 100 Resilient Cities network in 2013 and experience as a member has fed into our post-CES perspective on urban regeneration. In this context of heightened multi-hazard awareness and understanding, we are hopeful that recognition of the multi-hazard nature of low-lying seismically active coastal settlements will help local recovery and regeneration efforts, as well as transformations of settlements in similar coastal locations elsewhere, to produce better places to live for current and future generations, in line with the aspirations of UNEP's (1992) Agenda 21.

5. CONCLUSIONS

The multi-hazard assessment framework described in this paper, was conceived by collating and analyzing published information on hazard versus multi-hazard perspectives, plus observations from earthquake-flooding interactions in Christchurch following the CES, amongst other studies. The resultant initial analysis framework demonstrates that the effectiveness of any hazard assessment approach may be strongly contingent on recognition and identification of multi-hazard interrelations that can enhance, reduce or otherwise modify the effects any natural hazard event. While our approach was developed from local scientific and engineering observations in Christchurch, New Zealand, it is transferable for use by multiple stakeholders for supporting many types of multi-hazard assessment and resilience enhancement exercise, pre or post disaster, in seismically active, flood prone environments. Moreover, the broader approach and lessons learned from comparing hazards versus multi-hazards is transferable beyond the earthquake-flooding hazard nexus to the evaluation of different types of natural hazard phenomena in different multi-hazard environments.

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