Benchmarking household storm surge risk perceptions to scientific models in the Philippines

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Abstract
Household perceptions of hazards play an important role in mobilizing efforts for disaster risk reduction. This research aimed to examine perceptions of storm surge in the Philippines through a case study of the Municipality of Carigara located in the province of Leyte. Surveys from 1,093 households were collected asking about perceived storm surge exposure. Building vulnerability indicators were combined with storm surge inundation models and household perceptions to compare differences in storm surge risk. More than half of households in modelled inundation zones either did not know their exposure or believed they were not exposed to 2-m surge heights and above. While there was alignment between modelled and perceived risk of low-level storm surge events, our results show a significant disconnect between household perceptions and probabilistic models for larger storm surge inundation events, pointing to continued gaps in storm surge knowledge in the Philippines.

Keywords Storm surge · Natural hazards · Risk analysis · Philippines

1 Introduction

In low- and middle-income countries, disasters hinder sustainable development efforts and hamper hard won gains to reduce poverty (World Bank and United Nations 2010). Disasters claimed 1.23 million lives and inflicted $2.97 trillion (USD) in economic losses over the last two decades (CRED and UNDRR 2020). Globally, storms affect nearly one in five people and are the second deadliest type of natural hazard. Storm surge is a rise in sea level as a result of wind and atmospheric pressure differentials along coastlines which occurs in advance of coastal storms. For tropical cyclones, which include hurricanes and typhoons, drowning from storm surge is estimated to account for up to 90% of cyclone-attributed mortality (Keim 2008). Mortality from storm surge has decreased over the last several decades as a result of disaster risk reduction efforts in all regions globally except in South East Asia (Bouwer and Jonkman 2018). In the Philippines, which ranks among the top ten countries most affected by disasters—both in absolute number of people and standardized
relative to its population, typhoons accounted for 77% of disaster-related fatalities since 2000 (EM-DAT et al. 2020).

Despite the frequent occurrence of typhoons in the Philippines, which sees on average 20 typhoons pass through its waters each year, there remain challenges in reducing losses from storm surge. Typhoon Haiyan in 2013 highlighted gaps in knowledge of storm surge, by both scientists and local communities (Lagmay et al. 2015). There have been significant recent investments in storm surge modelling in the aftermath of Haiyan to develop more accurate inundation maps. However, there remain relatively few studies which cross-examine household perceptions against these scientific models to inform future disaster risk reduction strategies. The Sendai Framework for Disaster Risk Reduction, adopted in 2015 by United Nations member states, has advanced calls to understand disaster risk, highlighted as the first of our four priorities. The framework outlines a clear need to ‘To promote national strategies to strengthen public education and awareness in disaster risk reduction, including disaster risk information and knowledge….’ (UNISDR 2015, p. 15).

To address these gaps, we selected a case municipality in the Philippines to explore understanding of storm surge hazards and risk, seeking to answer the question: How do household perceptions of storm surge hazards compare with scientific models in the Philippines? The main objectives of this research were: (1) to quantify storm surge exposure for buildings within a case municipality and (2) to compare the resulting storm surge risk spatial patterns that arise from household hazard perceptions and scientific modelling. This research seeks to take stock of recent progress to raise awareness of storm surge hazards and assess how households perceive storm surge hazards in order to guide future disaster risk reduction efforts in the Philippines.

2 Background

We first provide an overview of disaster risk reduction concepts, examine the current state of disaster risk reduction efforts in the Philippines where this research is situated, and then review the existing knowledge on how households perceive storm surge hazards.

2.1 Disaster risk reduction concepts

Wisner et al. (2012, p. 22) define disaster risk as the product of hazard and vulnerability, where the term ‘vulnerability’ is used to denote ‘the degree to which one’s social status influence differential impact by natural hazards and the social processes which led there and maintain that status’. In other words, disaster risk can be viewed as a function of the potentially harmful natural event (the ‘hazard’) and a function of susceptibility to harm. Vulnerability offers an explanation of the uneven effects of disasters by accounting for physical, social, economic, and environmental conditions.

Gaillard and Mercer (2013) note two major conflicting views on disasters over the last century. The more prevalent conceptualization of disasters comes from the behavioural geography movement and emphasizes that ‘disasters result from extreme and rare natural hazards, and that affected people fail to “adjust” because their perception of risk associated to these natural events is insufficient’ as outlined by Burton et al. (1978) and Kates (1971). However, more recent views in line with the political ecology tradition take into account vulnerability and asserts that ‘disasters primarily affect those who are marginalized in everyday life and who lack access to resources and means of protection which are available to
others with more power’ as understood by Hewitt (1983) and Blaikie et al. (2014). Gaillard and Mercer (2013, p. 94) suggests that most disaster risk reduction strategies give primary attention to the former paradigm’s focus on the hazard, resulting in national policies which ‘emphasise scientific knowledge and national government intervention at the detriment of local actions’. Wisner et al. (1994, p. 5) stresses the importance of viewing disasters as a ‘complex mix of natural hazards and human action’, requiring a thorough analysis of the various social factors that affect the reasons behind people’s vulnerability to hazards, as opposed to uncontrollable events that occur separate to the social environment surrounding the affected people. The importance of vulnerability in disaster risk reduction is echoed by Birkmann (2013) who states that vulnerability gives important insights for understanding the differential impacts of natural hazards, as well as Weichselgartner (2001) who argues that the concept of vulnerability can act as a vehicle to explore a contextual approach to the reduction of losses due to disasters, suggesting that a reduction in vulnerability is a more effective way of decreasing damage and loss. The main challenge, however, is the integration of different types of information, knowledge, and experiences and the collaboration of scientists, practitioners, and policymakers (Thomalla et al. 2006).

There has been an increase in the use of vulnerability assessments in disaster risk reduction, but the analysis of physical vulnerability to hazards remains understudied (Kappes et al. 2012). While there is no standard method of assessing vulnerability, single-hazard approaches are commonly used in favour of more complex multi-hazard methods, although the importance of the latter has been emphasized by multiple sources such as UNISDR (2015), now the United Nations Office for Disaster Risk Reduction (UNDRR). Kappes et al. (2012) notes that in the context of assessing physical vulnerability, indicators are often regarded as hazard-specific and are a qualitative and relative measure of vulnerability, requiring the assignment of a scale based on importance. However, for single-hazard assessments, this method allows several characteristics to be analysed at once and is highly flexible. The capacity of a building to withstand hydrodynamic forces depends on a variety of attributes defined by each building’s unique structural characteristics (Tarbotton et al. 2015). Scholars have studied storm impacts, modelling both wind and storm impacts (Chaivutitorn et al. 2020). Despite significant research into hydrological hazards, there is a general absence of building-level vulnerability indicators specific to storm surge. However, there is a significant body of knowledge on vulnerability indicators for similar coastal hazards, namely tsunamis and dynamic flooding (Thouret et al. 2014; Jeong and Yoon 2018; Papathoma-Köhle et al. 2019). While others have noted differences in how tsunami and storm surge hazards impact buildings, predominantly stemming from differences in flow velocities (Dall’Osso and Dominey-Howes 2013), empirical studies of damage suggest there is significant overlap in how we might understand these hazards (Hatzikyriakou and Lin 2017, 2018).

2.2 The state of disaster risk reduction in the Philippines

The Philippine government has devoted significant resources to reducing disaster risk, developing policy and institutional mechanisms for disaster risk reduction as well as investing in research for disaster preparedness, management, and resilience (Alcayna et al. 2016). The Philippine Disaster Risk Reduction and Management Act of 2010 is the focal law which provides policies, frameworks, and plans for disaster risk reduction, establishing local councils and offices at the regional, provincial, municipal, and community levels that help carry the responsibilities of the National Disaster Risk Reduction and Management
Council (NDDRMC). However, the effectiveness of risk reduction actions relies heavily on the individual disaster management efforts from local municipalities. There remain challenges in communicating risk information with communities and ensuring awareness and sensitivity to hazards (Bollettino et al. 2020).

One of the more recent examples includes Typhoon Haiyan, which struck the Visayas region in 2013. Warnings of storm surge were broadcast on national television prior to Haiyan’s landfall; however, failure by local communities to evacuate and inadequate risk assessments resulted in one of the Philippines most devastating disasters in recent history. The storm caused over 6,300 deaths, injured 28,000, and affected more than 16 million people (NDRRMC 2014). Shortcoming were attributed to underestimation of inundation in previous hazard maps, with an estimated 68% of evacuation centres overwhelmed by storm surge in Tacloban—the most heavily affected city (Lagmay et al. 2015). However, many residents were not aware of the existence of these storm surge hazard maps beforehand, which were often only displayed centrally in municipal buildings and not available within communities. Yi et al.’s (2015) previous research in Tanauan found that while hazard maps for storm surge were available beginning in 2007, the strength of Typhoon Haiyan exceeded these estimations, with the flooded area extending inland by up to 330 m. Complacency by communities also resulted in many households who choose not to evacuate, while others were unfamiliar with ‘storm surge’ as a terminology, stating that ‘tsunami’ was a more familiar term, which led to poor understanding of early warning messages (Neussner 2014).

The Philippine Department of Science and Technology (DOST) initiated the Nationwide Operational Assessment of Hazards (NOAH) in 2012, just before Haiyan, with the goal of providing research and development to assist in disaster risk reduction and management. The initiative prepared extensive hazard maps including flooding, landslide, and storm surge inundation maps for all provinces. High-resolution topography was used to produce detailed maps which, along with advance warning, helped mitigate the loss of life in 2014 following Typhoon Hagupit (Lagmay and Kerle 2015).

2.3 Perceptions of storm surge

Public risk perceptions of hazards are an important element that shapes disaster policy and response (Peacock et al. 2005). There is a growing body of knowledge about perceptions of storm surge, with significant work dedicated to understanding awareness of the hazard characteristics (Esteban et al. 2016), sources of knowledge (Neussner 2014), and how warning messages are understood and interpreted (Yore and Walker 2020). However, much of the previous literature utilizes actual impacts from disasters, rather than examining the alignment (or lack thereof) between public perceptions and scientific models. While previous research has offered significant insight, retroactively assessing pre-disaster perceptions can be challenged and biased by the recency of disaster impacts—even years later. Others have focused on this gap, such as Valenzuela et al (2020), who focused on the case of communities with little prior experience to examine perceptions of storm surge risk in the province of Palawan, finding that communities underestimate their risk. However, there remains a gap in unpacking perceptions to understand the nuances of perceptions across different population segments and differences across severity of storm surge in the Philippines. More broadly, there is a need to position perceptions in the context of risk, integrating vulnerability to understand the differential of storm surge perceptions and consequences on potential impact (Lagmay and Racoma 2019).
3 Methods

This research sought to compare building-level storm surge risk formulated from household perceptions and scientific modelling to better understand how communities view coastal hazards in the Philippines. We bounded our study to the Municipality of Carigara which is located in the province of Leyte. The municipality has a population of 51,345, as reported by the Philippines Statistics Authority in the most recent 2015 census (PSA 2015). Roughly half of Carigara’s population resides in urban areas along its coastline, facing frequent hydrological hazards. The province of Leyte experienced devastating storm surges during Typhoon Haiyan in 2013. Carigara was not heavily affected by surges during Haiyan, but this setting allowed for a case where there has been public discourse on the potential risk of storm surge. Other characteristics of Carigara, such as its demographics, also make it broadly comparable to many coastal municipalities in the Philippines.

We conceptually defined storm surge risk for individual buildings as a function of the hazard and building vulnerability as follows:

\[ \text{Storm Surge Risk} = \text{Hazard} \times \text{Vulnerability} \]  

(1)

where the hazard was described by the storm surge inundation depth and vulnerability was the susceptibility of a given building to damage. Vulnerability, or fragility, curves are commonly used to assess how buildings will perform when exposed to dynamic flooding; however, these curves rely on an empirical relationship between a hazard’s magnitude and observed loss for structures. There are currently few such curves that have been developed for storm surge, and at the time of study, none that are publicly available and specific to the Philippines. As such, we opted to employ an indicator-based approach to measure building vulnerability based on a derivation of the Papathoma Tsunami Vulnerability Assessment (PTVA-2) model (Dominey-Howes et al. 2010). We only focus on physical building risk, but also acknowledge the important role of social vulnerability which was beyond the scope of this specific study. An overall of our risk modelling approach is shown in Fig. 1.

The PTVA model provides a framework to assess building vulnerability based on measurable attributes. The first version of the PTVA model (PTVA-1) (Papathoma-Köhle and Dominey-Howes 2003) was one of the first attempts to use GIS to provide a comprehensive tsunami vulnerability assessment of the built environment (Tarbotton et al. 2012). Several updated versions of the PTVA model have since been created; in particular, post-event surveys and damage assessments following the 2004 Indian Ocean tsunami allowed the PTVA model to be tested and validated subsequently leading to the development of the PTVA-2 (Dominey-Howes et al. 2010). The PTVA-2 model differs from its predecessor in that inundation depth is explicitly included in the calculation. PTVA-3 and 4 further revise and validate the vulnerability indicators used in previous models through use of the Analytical Hierarchy Process (AHP) (Dall’Osso and Dominey-Howes 2013). The introduction of these latter models add sets of indicators related to water intrusion (Dall’Osso et al. 2009) which require significantly more ground survey data. While latter iterations of the PTVA have been shown to reflect more nuanced building vulnerability, earlier iterations remain effective indicators that are well suited in data-limited contexts, having been validated in numerous settings.

Storm surge hazards have been largely understudied, and in the absence of storm surge vulnerability indicators, the PTVA-2 assessment produced for tsunami hazards was adapted to measure building vulnerability in this research due to the similar nature of hazards that derive from hydrostatic and hydrodynamic forces (Papathoma-Köhle et al. 2019). As
others have noted (Gentile et al. 2019), the PTVA models can be used to assess risk, given their inclusion of not only building attributes, but also the hazard. Two sets of hazard exposure data formed the basis for comparison in this research—storm surge models produced through the Philippines Nationwide Operational Assessment of Hazards (Project NOAH) and local household surveys conducted in the Municipality of Carigara.

### 3.1 Storm surge hazard exposure

Project NOAH storm surge hazard models were produced in 2015 under the Philippines Department of Science and Technology (DOST), prompted by the overwhelming damage and loss of life due to storm surge generated by Typhoon Haiyan in 2013. These models rely on an archive of typhoon tracks kept by the Japan Meteorological Agency (JMA)
covering 1948 to 2013. In conjunction with the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), simulations were generated in the JMA Storm Surge Model using the tracks of historical typhoons that crossed the Philippine Area of Responsibility (PAR). The resulting hazard maps, depicted in Fig. 2, produced show predicted storm surge inundation. Four Storm Surge Advisory (SSA) maps were generated based on surge heights of 1–2 m (SSA1), 2–3 m (SSA2), 3–4 m (SSA3), and 4–5 m (SSA4). Each map is categorized by low (0–0.5 m), medium (0.5–1.5 m), and high (>1.5 m) inundation zones (Lagmay et al. 2015; Lapidez et al. 2015). These approximately correspond to return periods of 25, 40, 60, and 90 years, respectively (Irish et al. 2008; Neussner 2015). The storm surge models used did not consider sea level rise projections. Furthermore, building obstructions were not considered in limiting inundation extents. The original inundation maps were missing some data along coastlines due to different coastal boundaries used when they were created. We interpolated and extended these to match the coastline boundaries used in this study for consistency.

In addition to storm surge models, we also collected data on household perceptions with assistance from the Carigara Municipal Disaster Risk Reduction and Management Office (MDRRMO). In coordination with local Barangay Disaster Risk Reduction and Management Committees (BDRRMCs), a household hazard awareness survey on perceptions of storm surge, flood, and landslide hazards was completed in 2018. This survey collected data from 2,743 households who were selected using stratified random sampling from a list of households known to be residing in the Municipality of Carigara. Barangays, which represent the lowest administrative division in the Philippines, were used as strata to ensure distribution of responses across the municipal population and so that disaggregated data could be compared across communities. BDRRMC members and Barangay Health Workers (BHWs) assisted in collecting the survey data, who asked questions in Waray, the local language of respondents. Communities located well outside the DOST inundation extents, located in upload regions, were not asked about their exposure to storm surge. Communities on the verge of expected maximum inundation extents were still surveyed. Ethical

Fig. 2 Storm surge inundation zones
approval was granted by University of Sydney Ethics Committee under protocol number 2019/423.

Households were asked whether their home was affected by storm surge and responses recorded on paper, which were then encoded into a database. Respondents were asked to consider a maximum case of storm surge affecting their home. If a household stated their home was affected, they were asked a follow-up question, whether they believed inundation would be above their head height (1.5 + meters), knee to shoulder height (0.5–1.5 m), or below knee height (0–0.5 m). The inundation depths asked corresponded to DOST maps for comparison. Alternatively, households could have stated that their home was not exposed or that they did not know their level of exposure. A total of 1,359 household responses were recorded for storm surge perceptions, covering approximately 9% of the total municipality population. These responses were then linked to known building locations. Forty-six households could not be paired with a building location, due to ongoing coastal resettlement of some households and non-matching household names.

3.2 Building physical vulnerability indicators

Following the methodology outlined by Dominey-Howes et al. (2010), the PTVA-2 model was adapted to calculate building risk scores for storm surge hazards. Research has indicated that physical vulnerability indicators for buildings are similar across different types of hazards, particularly hydrological hazards (Papathoma-Köhle et al. 2019). In the absence of specific building vulnerability indicators for storm surge, we modified the PTVA-2 model. Two indicators—building condition and building surroundings—were removed. Building condition is likely to have been highly correlated with building materials in the studied context, and building surroundings, such as walls, were better captured by a combined measure which focused on density of buildings around a structure. Furthermore, both indicators had relatively low weighting in the original model.

According to 2015 census data, the latest available at the time of publishing (PSA 2015), outer wall materials for residential structures across the municipality consisted of 38% concrete or masonry, 35% wood, 17% used a mix of wood and masonry, 7% galvanised iron, and the rest a smaller minority of other materials. A large majority of roofing was galvanised iron. Most commercial buildings in central areas were masonry construction. A sample of common building typologies is shown in Fig. 3.

The physical vulnerability indicators used in this study were gathered from a variety of sources including local authorities, scientific bodies, and OpenStreetMap (OSM), shown in

![Example building typologies](image-url)
Table 1. The following sections outline how the indicators from the PTVA-2 model have been adapted and collected for use in this study.

### 3.2.1 Flow depth

Flow depth is a function of the intensity of the storm surge and exposure to the hazard. It was considered the most dominant indicator as it is a representation of distance to shore which most closely correlates with surge characteristics (Xian et al. 2015). DOST storm surge inundation maps and household surveys were used as the basis for this indicator. Buildings were assigned exposure levels for each SSA scenario using InaSAFE, a QGIS plugin.

### 3.2.2 Building material

Yi et al. (2015) conducted field surveys after Typhoon Haiyan in the Municipality of Tanauan, located nearby to our study context, comparing building damage to building materials that included: concrete, wood and masonry. While concrete structures were severely damaged, wood and masonry houses were completely destroyed and washed away. Building material data for 8,292 buildings in Carigara were collected by the MDRRMO in a survey in 2018. Buildings were classified, through visual inspection by enumerators, into four material types: concrete (type 1), concrete and wood (type 2), wood and lightweight materials (type 3), and scrap and salvage materials (type 4). Concrete structures were defined to have a slab roof and masonry walls, while concrete and wood structures had timber roofs or masonry skirt walls with plywood siding. Wood and lightweight materials were all timber structures with either plywood or thatch siding. Finally, scrap and salvage materials lacked structural elements, such as posts, and were made of corrugated steel sheeting, plywood, or other poor-quality materials. Building material survey data were not available for 195 of the households surveyed on storm surge perceptions (17.84%). Visual inspection of this small number of houses missed from the initial survey was conducted using Google Street View and material classifications assigned using the same criteria noted above. Imagery from Google Street View was deemed to be of good quality and suitable for classifying building material digitally without needing to re-enter the field. For all other buildings missing material...
data, concrete and wood (type 2) was assumed—the most common locally used building construction.

3.2.3 Number of floors

Multiple floors allows the possibility of vertical evacuation, where occupants are at a significantly decreased risk of injury or death and are also associated with more robust construction and load bearing capability compared with single-storey buildings. The building heights were approximated in QGIS by taking the median height of the difference between the digital surface (DSM) and terrain (DTM) models within OpenStreetMap building footprints. Light Detection and Ranging (LiDAR) data of Leyte and its surrounding islands were provided by the University of the Philippines as part of the Disaster Risk and Exposure Assessment for Mitigation (DREAM) and Phil-LiDAR programs from 2014 to 2017 (Paringit and Morales Jr 2017). The elevation datasets were produced with horizontal and vertical accuracies of 0.5 and 0.2 m, respectively. Median building height was used to counteract the effects of possible overhanging foliage and misaligned building footprints. Each building was then classed into single or multi-storey using a maximum single-storey height of five metres. While previous research has suggested possible lower damage for three-storey and higher structures (Suppasri et al. 2013), few of these building actually existed in our study site, thus our reason to retaining the original PTVA-2 indicator by binary division at two or more storeys. This methodological decision is also consistent with previous studies of storm surge damage (Xian et al. 2015).

3.2.4 Building density buffer

The PTVA-2 assessment was originally derived in locations where organized building rows from the coastline could be determined (Dominey-Howes et al. 2010). However, this is only effective for similarly sized buildings with regular spacings and is often inaccurate for buildings further inland which may consist of structures which are spaced far apart. The building density buffer used in this study improves upon building row indicator in the original PTVA-2 by factoring variability in building sizes and urban density and is more
appropriate for the more irregular housing distribution found in the Philippines. A building density buffer, depicted in Fig. 4, was used as a ratio of open area not occupied by buildings (A2) to the area of a buffer zone in the direction of storm surge flow (A1). A buffer distance of 100 m, the depth of a typical city block, was used to capture local shielding effects of surrounding structures radially. In the absence of a detailed hydrological model, the flow direction was estimated to be the direction of the shortest distance to the coastline (noted by the dashed red line in Fig. 4). To mitigate the effect of coastline variability, the coastline was smoothed and offset 50 m.

### 3.2.5 Building shape and orientation

Previous field surveys have identified a clear correlation between the shape and orientation of a building and the impact of hydrodynamic forces on the structure (Wüthrich et al. 2020). Buildings with more regular footprints experience less damage than long rectangular, or irregularly shaped buildings whose long face is oriented perpendicular to the direction of flow. Scale model testing reinforces this as the surface area perpendicular to the flow is larger and exposed to greater external pressure (van de Lindt et al. 2009). We draw on the building classification system proposed by Alberico et al (2015). We modified the classification so that oblong buildings with the short-face oriented perpendicularly to the direction of flow have been separated to differentiate them from regular building footprints to take into account the variability in flow direction (regular shapes react equally to flows in all directions), depicted in Fig. 5.

The footprint of each building in Carigara was fit into rectangular bounding boxes, from which the width, length, and orientation of the building were calculated. Regular building shapes were classified as having a width to length ratio of 1 to 1.5 to account for small discrepancies in building footprints. Irregularity was determined by area discrepancies between the original building footprint and that of the minimum bounding box. The orientation of the building was also compared with the estimated direction of flow calculated previously for building density buffer, allowing oblong and irregular structures to be classified as having its long face or short face to the flow.

![Classification for building shape and orientation](image-url)
3.2.6 Land cover

The presence of vegetation dissipates storm surge hazards (Sheng et al. 2012), influencing the damage to structures. Land cover for each building was estimated using OSM land use data where buildings in ‘residential’ areas were defined as ‘urban’ and having little to no vegetation, and all other areas assumed to have some level of vegetated cover. This is a simplified method of estimating vegetated cover where buildings within the main urban district of Carigara were deemed to have a considerably lower presence of vegetation than those outside.

3.3 Building risk assessments

We first calculated risk scores using the selected building vulnerability indicators, followed by statistical analysis of building-level risk to compare household perceptions and scientific models. To calculate risk, InaSAFE—a QGIS plugin—was used to assign exposure values to buildings obtained from OSM for all buildings in Carigara. Physical vulnerability indicators were similarly calculated and assigned to their corresponding building, which combined weightings and indicators into risk scores. There was a total of 16,998 buildings within the municipality, with 1,313 building-paired household hazard awareness responses for storm surge. Excluding 220 households which answered ‘I don’t know’, there were 1,093 households with a response for storm surge hazard perception. The risk scores for these buildings were isolated to compare household perception with scientific modelling.

The building indicators in this model were identified and weighted according to their contribution to the overall building vulnerability using expert judgement by Papathoma (2003). The method used in this research adapts vulnerability indicators from the PTVA-2 model to create a simplified estimation of building risk to storm surge, calculated via a weighted sum.

\[ R = w_1 b v_1 + w_2 b v_2 + w_3 b v_3 + \cdots + w_n b v_n \]

(2)

where building storm surge risk \((R)\) is calculated by aggregating each vulnerability indicator \((b v_n)\) multiplied by a weighted factor \((w_n)\). The list of indicators and their scores classified by description are shown in Table 2. To calculate the risk score for each building, indicator scores must first be standardized to a scale between 0 and 1 to allow for inter-attribute manipulation (Dall’Osso et al. 2016). To do this, each score was divided by the highest possible value for that indicator. For example, for flow depth, the score may be 2 (indicating a flow depth between 0.5 and 1.5 m) and is divided by 3 (which is the maximum possible score for this indicator). Our lowest possible risk score based on all indicators was 11.47, while the highest score was 31.00.

We also classified our risk scores using the ranking system suggested by Dominey-Howes et al. (2010). The range of possible scores from 11.47 to 31 were divided into five equal intervals ranging from low (11.47–15.37), medium–low (15.37–19.28), medium (19.28–23.19), medium–high (23.19–27.09), and high (27.09–31.00). Distributions of the calculated building risk scores, for each of the four considered storm surge scenarios, are shown in Fig. 6. While a relatively small number of structures were at risk in lower scenarios, this expanded significantly in SSA3 and SSA4. As can be seen in higher scenarios, inundation level alone does not explain building risk.
Table 2  Building vulnerability indicators, weightings (w), and scores

| Flow depth | Building density buffer | Building material | Number of floors | Building shape and orientation | Land cover |
|------------|-------------------------|-------------------|------------------|-------------------------------|------------|
|            | w₁ = 8                  | w₂ = 7            | w₃ = 6           | w₄ = 5                        | w₅ = 4     | w₆ = 1 |
| Exposure   | Score                   | Density           | Material         | Storeys                       | Description | Score | Type    | Score |
| High (> 1.5 m) | 3   | Least dense 1          | Scrap and salvaged materials | 4    | 1 storey 2 | Irregular (long face to flow) | 5 | Urban 2 |
| Medium (0.5–1.5 m) | 2   | Most dense 0.5         | Wood and light materials | 3    | 2 or more storeys 1 | Irregular (short face to flow) | 4 | Non-urban 1 |
| Low (0–0.5 m)     | 1   | Concrete and wood     | Concrete and wood | 2    |               | Oblong (long face to flow) | 3 |               |
|                 |      | Concrete              |                  | 1    |               | Oblong (short face to flow) | 2 |               |
|                 |      |                      |                  |      |               | Regular              | 1 |               |
3.4 Comparison of hazard and risk perceptions against scientific models

We first compared hazard exposure between the surveyed households and inundation extents of the considered four storm surge models. This included summary statistics on the number of buildings exposure based on both perceived and modelled estimates as well as the corresponding risk of these structures. We also reported separately on the number of households that did not believe their home was exposed to any level of inundation but fell within at least one of the models. To examine more closely trends in conflicts between perceptions and models, we also disaggregated survey responses to examine households that either under- or overestimated their risk.

4 Results

This research aimed to improve understanding of household perceptions of storm surge in the Philippines, comparing household awareness and scientific modelling of hazard exposure. Combining hazard exposure with building vulnerability indicators, risk scores were calculated for structures in Carigara. We first examine differences in household perceptions and scientific models of exposure, before extending this analysis to compare risk.

From the 1,093 survey responses, 444 households (41%) reported being exposed to storm surge hazards. Thirty-eight of the households surveyed were located within the inundation zone of SSA1, 480 households located in SS2 extents, 697 households in SS3 extents, and 709 households in SSA4 extents. An overall summary of exposure and risk for the four SSA models and household perceptions is shown in Fig. 7. We found that overall counts of household perceptions were most similar to SSA2 exposure, equivalent to a two- to three-meter surge. In context, the SSA2 level was equivalent to a return period of 40 years. However, there was both underestimation and overestimation of storm surge...
exposure, suggesting that awareness was not uniform across communities. Households in some communities well outside the highest modelled inundation zones reported a medium to high perceived hazard exposure, while some households located close to the coastline reported being unaffected.

We found that households residing in coastal areas had the highest levels of storm surge awareness, with a growing disconnect for larger storm surge events. For example, only three of the 38 households sampled (7.89%) in SSA1 inundation zones believed they were not exposed to storm surge hazards. In contrast, 216 of the 480 households surveyed in SSA2 inundation zones (45.00%) believed they were not exposed. Similar perceptions of non-exposure were found for SSA3 (46.62%) and SSA4 (47.39%). The differences between modelled and perceived exposure were stark—in SSA2 extents 96.29% of households who stated they were not exposed were located in medium inundation zones (0.5–1.5 m). For SSA3 and SSA4, 77.54% and 96.73% of households stating they were not exposed were located in high inundation zones (1.5 m +). There were also many households, 220 (20.1%), who stated they did not know their exposure.

Fig. 7 Comparison of storm surge exposure and risk

Fig. 8 Risk score histogram for all SSA-affected buildings
While comparison of modelled and perceived storm surge exposure is important, the consequences of differing exposure are not equal across households. For example, the corollary is significant for two households who underestimate their exposure but reside in differing quality of housing. It is therefore critical that we understand not only exposure, but how these perceptions are positioned in a broader understanding of risk. We modelled risk for all buildings within the DOST inundation zones. Under the most severe model—SSA4, 7,815 buildings (46% of all buildings in Carigara), were located within the inundation extents and would be affected, with 78% of buildings at medium–high or high risk. The distribution of exposure and risk for all buildings in Carigara is depicted in Fig. 8.

Our results showed an increasing risk gap between household perceptions and scientific models at higher magnitude storm surge events. A summary of the disaggregated building risk between household perceptions and SSA models is shown in Table 3. For the smallest scenario considered (SSA1), risk scores based on perceptions and scientific models were in alignment for nearly half (49%) of households surveyed. The percent of households where perceptions and models resulted in equivalent risk continued to decrease for larger storm surge events from 29% (SSA2) to 24% (SSA4). The percent of households that underestimate their risk, in contrast, rose from 20% (SSA1) to 76% (SSA4). Nearly a third (31%) of households overestimated their risk in the lowest scenario model (SSA1) with a decreasing trend to 0.3% (SSA4). There was also a trend that those underestimating their risk were located in medium–high areas of risk, 49.9% of households in SSA4 for example.

| Table 3  | Storm surge household perception risk compared to models |
|----------|---------------------------------------------------------|
| **Modelled Storm Surge Risk** | Low (%) | Medium–Low (%) | Medium (%) | Medium–High (%) | High (%) | Total (%) |
| SSA1 (N = 35) | Underestimate | 0.0 | 0.0 | 8.6 | 11.4 | 0.0 | 20.0 |
| SSA1 (N = 35) | Equivalent Risk | 0.0 | 2.9 | 34.3 | 11.4 | 0.0 | 48.6 |
| SSA1 (N = 35) | Overestimate | 0.0 | 2.9 | 14.3 | 14.3 | 0.0 | 31.4 |
| SSA2 (N = 264) | Underestimate | 0.4 | 3.0 | 36.7 | 8.3 | 0.8 | 49.2 |
| SSA2 (N = 264) | Equivalent Risk | 0 | 3 | 19 | 7 | 1 | 28.8 |
| SSA2 (N = 264) | Overestimate | 0 | 2 | 18 | 2 | 0 | 22.0 |
| SSA3 (N = 372) | Underestimate | 0.0 | 2.4 | 24.2 | 42.5 | 1.9 | 71.0 |
| SSA3 (N = 372) | Equivalent Risk | 0.0 | 0.8 | 10.8 | 13.2 | 0.5 | 25.3 |
| SSA3 (N = 372) | Overestimate | 0.0 | 1.1 | 2.7 | 0.0 | 0.0 | 3.8 |
| SSA4 (N = 373) | Underestimate | 0.0 | 0.5 | 23.3 | 49.9 | 1.9 | 75.6 |
| SSA4 (N = 373) | Equivalent Risk | 0.0 | 0.0 | 9.1 | 14.5 | 0.5 | 24.1 |
| SSA4 (N = 373) | Overestimate | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0 |
5 Discussion

Our findings raise two disconnects in household perceptions of storm surge. First, households who do recognize storm surge as affecting them consistently underestimate their exposure. Twenty percent of households underestimated their exposure for smaller storm surge events (SSA1), while 76% of households underestimated their exposure for larger events (SSA4). We also found that those underestimating exposure were at higher risk for larger surge events. Secondly, we found that more than half of households in storm surge exposed regions were unaware of the risks posed to them. This reinforces that storm surge continues to be a poorly understood hazard to many households. While it was promising that many households were able to identify what storm surge was, our results indicate that households had a difficult time conceptualizing storm surge impacts and particularly extreme events that have longer return intervals. This has important implications for continued disaster risk reduction.

5.1 How to increase storm surge awareness?

A spatial-based approach is ideal for gathering data to produce visual outputs such as risk maps which have the capacity to improve community awareness and sensitivity to hazards as well as disaster recovery and response for local government and emergency services. Hazard maps such as those produced by the DOST facilitate public hazard communication by depicting information on the geographic extent of estimated inundation zones. The risk maps produced in our study go beyond hazard exposure to provide a visual tool to represent localized estimations of risk to increase public knowledge and understanding of the potential impact of storm surge hazards at a building level. These maps have the potential to increase household capacities of recognizing risk, as well as the way different building characteristics affect them. Houston et al. (2019) emphasize the increasing use of digital, interactive maps in risk communication, where maps that depict hazards at local levels have greater meaning and are more relevant to individuals, especially when utilizing pan-and-zoom interfaces which encourage users to explore risks near recognizable landmarks and personally significant locations. There is also evidence to suggest that viewing these maps helps minimize differences in hazard perception across communities to generate a shared understanding (Sanders et al. 2020). This aligns with Lagmay et al. (2017, p. 14) who reinforces that getting individuals in the Philippines to identify with the problem is crucial ‘since awareness is the first step towards building disaster resilient communities’.

5.2 Growing importance of storm surge awareness

Rising sea levels and warmer temperatures due to climate change are increasing the frequency and intensity of typhoon activities, intensifying the effects of storm surges (Dasgupta et al. 2009). With increases in coastal population growth and storm surges moving further inland, the UNDRR predicts that at the global level, there will be an increased risk of coastal flooding and ‘changes in the mean sea-level, storm-surge levels, the frequency of storm surges, wave action and water temperature/volume will have tremendous implications for the underlying assumption of the long-term risk models currently in use’ (UNDRR 2019, p. 97). Creating awareness of these hazards remains a vital first step to reducing risks and promoting sustainable development.

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5.3 Limitations

Some assumptions were made to supplement missing indicator data. Buildings missing heights due to gaps or inaccuracies in LiDAR data were assumed to be single-storey structures. As part of our adaptation of the PTVA model, we replaced an indicator for building density buffer that was better suited to the local conditions. Future studies could use post-event field studies to confirm its applicability, but we believe this represents an advancement in measuring vulnerability. More broadly, in the absence of indicators that are specific to the Philippines and have been validated, we believe this provides a reasonable starting place to assess building vulnerability. The use of a tsunami-derived vulnerability indicator set is currently the best available option at present, but future work should seek to develop and validate storm surge-specific vulnerability indicators.

We also recognize that we have narrowly defined risk in terms of only physical building attributes and that there are other aspects of vulnerability which are important for a holistic picture of disaster risk. Social vulnerability factors such as age, gender, disability, income, and education level are also important dimensions affecting perceptions of risk and would extend on the findings of this work. Access to resources, historical and cultural heritage and political economy may overcome physical vulnerability and these factors should also be examined.

6 Conclusion

This research aimed to assess community awareness of storm surge, addressing gaps in our understanding of how households perceive a hazard that is a leading cause of death from disasters in the Philippines. While we found alignment between local perceptions and low strength, regular storm surge events (SSA1), significant differences were found for increasingly severe storm surge events. With more than half of households in the selected municipality unaware the potential risk to their homes, our results point to a need to continue expanding education programs on storm surge. Our research provides an improved understanding of the current level of hazard awareness among communities, quantifying these perceptions across different levels of severity. The maps produced generate high-resolution risk distribution maps which have the potential to improve community resilience and education, providing a model which other municipalities can expand using open data, such as that sourced for this work. These maps can provide the knowledge to underpin decision making and planning for local government and emergency services.

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Declarations

Competing interests  The authors have no relevant financial or non-financial interests to disclose.

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