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ORIGINAL PAPER

Community disruptions and business costs for distant tsunami evacuations using maximum versus scenario-based zones

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Abstract Well-executed evacuations are key to minimizing loss of life from tsunamis, yet they also disrupt communities and business productivity in the process. Most coastal communities implement evacuations based on a previously delineated maximum-inundation zone that integrates zones from multiple tsunami sources. To support consistent evacuation planning that protects lives but attempts to minimize community disruptions, we explore the implications of scenario-based evacuation procedures and use the California (USA) coastline as our case study. We focus on the land in coastal communities that

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is in maximum-evacuation zones, but is not expected to be flooded by a tsunami generated by a Chilean earthquake scenario. Results suggest that a scenario-based evacuation could greatly reduce the number of residents and employees that would be advised to evacuate for 24–36 h (178,646 and 159,271 fewer individuals, respectively) and these reductions are concentrated primarily in three counties for this scenario. Private evacuation spending is estimated to be greater than public expenditures for operating shelters in the area of potential over-evacuations ($13 million compared to $1 million for a 1.5-day evacuation). Short-term disruption costs for businesses in the area of potential over-evacuation are approximately $122 million for a 1.5-day evacuation, with one-third of this cost associated with manufacturing, suggesting that some disruption costs may be recouped over time with increased short-term production. There are many businesses and organizations in this area that contain individuals with limited mobility or access and functional needs that may have substantial evacuation challenges. This study demonstrates and discusses the difficulties of tsunami-evacuation decision-making for relatively small to moderate events faced by emergency managers, not only in California but in coastal communities throughout the world.

Keywords Tsunami · Evacuation · Response · California · Business · Vulnerable populations

1 Introduction

Evacuations are instrumental to minimizing loss of life from tsunamis, including those self-initiated in a matter of minutes for local tsunamis and others coordinated by public safety officials over several hours for distant events. Although necessary for saving lives, evacuations also disrupt communities and economies. Manufacturers cease production, medical professionals interrupt their care for the sick or infirm, stores close and customers leave the area, schools shut down, many municipal activities stop, public safety officers are redirected from other duties to coordinate evacuations, and shipping is stopped or slowed because of overloaded road networks.

Other complicating factors related to the impact of tsunami evacuations are potential inconsistencies in how neighboring jurisdictions respond, especially for small to moderate tsunamis. For example, during the March 11, 2011, Tohoku tsunami, hundreds of people in Santa Cruz County (California, USA) disregarded official guidance issued by public safety offices and instead went to the harbor waterfront to see the tsunami arrival, whereas hundreds of residents in neighboring Monterey County evacuated to the Santa Cruz Mountains to a 300-m elevation. This inconsistency of an all-or-nothing evacuation response in two neighboring counties resulted from the uncertainty of the potential extent of tsunami inundation and caused additional stress on response agencies, as well as exposed people to potentially dangerous conditions (Wilson et al. 2013).

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Much has been written on the economic costs of damages caused by tsunamis (e.g., Papathoma et al. 2003; Toya and Skidmore 2007; Mimura et al. 2011; Jayasuriya and McCawley 2008; Wein et al. 2013); however, there is little on the topic of evacuations costs, especially for situations when tsunami waves were not as large as that of the maximum potential event determined for a coastal area. Cox (1977) estimated the costs of evacuating low-lying areas of the Hawaiian coastline in response to a tsunami warning at approximately \$3.0 million (adjusted to 2016 dollars). This estimate assumed an evacuation period of 3 h during a normal workday and included costs to the private sector (e.g., waterfront operations, hotel and retail establishments, wholesale businesses, and energy firms) and the public sector (e.g., state services, schools, and county services). A tsunami evacuation of Waikīkī Beach on southern Oahu Island in 1986 was estimated to cost approximately \$86.2 million (2016 dollars) (Bernard et al. 2006). Bernard (2005) estimated costs of evacuating parts of Hawaii in response to a 1996 warning at approximately \$88.2 million (2016 dollars).

The exact location, magnitude, and timing of the next tsunamigenic earthquake cannot be predicted; therefore, tsunami-evacuation maps typically reflect a single worst-case scenario (e.g., Walsh et al. 2000), a maximum zone that represents several tsunami sources (e.g., Wilson et al. 2008), or, in rare cases, multiple zones to identify worst-case scenarios for both local and distant tsunamis (e.g., Oregon Department of Geology and Mineral Industries 2013). The primary purpose of an evacuation map is to save lives; therefore, the use of composite maximum zones or worst-case scenarios to estimate the extent of inundation in a community is an attempt to minimize any surprises during future events, regardless of the actual magnitude and location of the generating earthquake or of environmental conditions at the time (e.g., wave setup or tidal stage). In addition, educating and preparing an at-risk population for tsunami evacuations relative to a single zone is challenging and will become more challenging with additional evacuation zones for various scenarios.

As the science and technology of earthquake and tsunami monitoring, inundation modeling, and warning communication improve, especially for distant source tsunamis with more time for response, it is worth considering how to define a recommended evacuation zone that protects populations, but also minimizes community disruptions. For example, State officials in California (USA) are working with community leaders to develop tsunami “playbooks” that provide guidance to local practitioners on various evacuation zones for distant tsunamis (California Geological Survey 2014; Wilson and Miller 2014). This will provide secondary evacuation options for emergency managers, which could ostensibly reduce over-evacuations and limit the impacts of an evacuation to just the people that are directly threatened by a particular tsunami. It is an attempt to protect lives while simultaneously minimizing community disruptions. Currently unknown is how much a transition from evacuations based on maximum zones to scenarios may minimize community disruptions. This information can provide the business case for such a transition and quantify the benefits of further investments to implement it.

The objective of this paper is to estimate the community and business disruptions associated with evacuating a maximum tsunami zone, instead of smaller scenario-based zones. This analysis focuses on a distant tsunami scenario in which waves would materialize; therefore, lives are threatened, but the extent of inundation is far less for some coastal communities than portrayed in a published maximum-evacuation zone based on the combination of potential inundation from multiple sources. Warnings with no subsequent inundation (i.e., “false alarms”) likely will become rare due to improvements in monitoring technology and in the science of tsunami generation and propagation; however, the potential for over-evacuations will persist due to the difficulty in predicting with absolute certainty the extent of inundation during an event. Scenario-based tsunami-evacuation

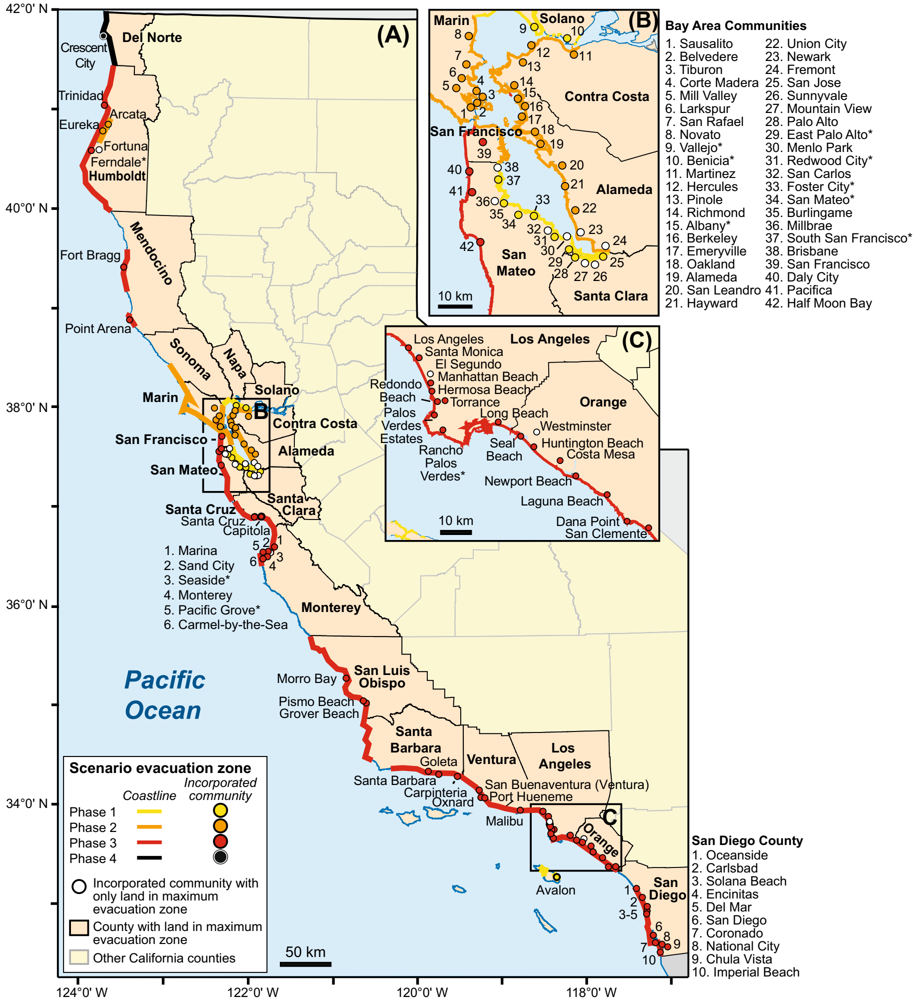

Fig. 1 Study area maps of incorporated cities and counties with land in the maximum tsunami-evacuation zone of **a** the state of California, **b** the Bay Area region of California, and **c** Los Angeles and Orange counties. Communities with *asterisks* have residents and/or businesses in the maximum tsunami-evacuation zone, but not in the scenario-based evacuation zone. Evacuation phase assignments for the coastline and incorporated communities are based on assumptions summarized in Fig. 2 for a tsunami associated with a Chilean earthquake scenario

planning is in its infancy in the USA, and there are still substantial warning coordination, communication, outreach, and response planning aspects to be addressed at multiple levels of government. Therefore, we do not profess to offer an exhaustive estimate of social and economic costs to justify an end to evacuation policies tied to maximum zones. Instead, we focus on introducing concepts for gauging the implications of various evacuation policies and the potential role of geospatial and economic analysis in their future implementation.

To explore community disruptions from distant tsunami evacuations, we focus on the State of California (USA), which has a maximum tsunami-evacuation zone (Fig. 1) and is currently developing additional, smaller-than-maximum-evacuation zones to provide guidance to local officials (Wilson and Miller 2014). The maximum zone is the current standard evacuation zone and is based on the maximum amount of inundation that is expected based on a composite of inundation from 12 to 15 tsunamigenic sources for a given locality, which is then delineated after discussions with local emergency managers (Wilson et al. 2010). Although there are many possible tsunami sources for California around the Pacific Ocean, we use a scenario developed for statewide evacuation planning that characterizes evacuation zones for a hypothetical yet plausible tsunami associated with an M_w 9.0 megathrust earthquake west of Chile (State of California 2016). First, we assess the number of residents that are in the maximum-evacuation zone but not in the scenario-evacuation zone. Second, we estimate the sheltering costs of this group for both the public sector (e.g., shelters operated by local governments or other organizations) and individual households (e.g., personal expenses related to commercial lodging and food). Third, we identify businesses or organizations in this area that could have substantial evacuation challenges, such as schools and hospitals. Fourth, we describe the short-term business impacts, in terms of economic output, labor income, and employment, which would temporarily stop during an evacuation. Finally, we examine impacts by business sector to determine which businesses may be able to recoup losses from a short-term disruption (e.g., manufacturing) and which are less likely to recoup losses because of the ephemeral nature of transactions (e.g., restaurants, retail). This analysis is intended to serve as a foundation for discussions of evacuation policies and procedures that protect lives while also minimize community disruption, both in California and in other coastal areas worldwide that also struggle with this issue.

2 Tsunami-evacuation planning in California

Situated on the seismically active Pacific Ocean basin, the State of California has experienced inundation and related coastal damage from several tsunamis in the past, including tsunamis associated with the 1946 M_w 8.1 Aleutian, 1960 M_w 9.5 Chile, 1964 M_w 9.2 Alaska, 2010 Chile M_w 8.8, and 2011 Tohoku M_w 9.0 earthquakes. In each of these events, the California coast experienced a series of damaging tsunami waves several hours after a distant (or "far-field") earthquake—approximately 4 h in the 1964 event and more than 10 h for the Tohoku and Chilean events (Lander et al. 1993; Wilson et al. 2013). Loss of life has been low from recent distant events because of the large amount of time between the earthquake and the wave arrival, as well as the existence of federal tsunami warning centers that transmit alerts and detailed wave heights and arrival times of incoming waves. Therefore, distant tsunamis primarily represent economic threats related to damage to ports and harbors (National Geophysical Data Center/World Data Service 2016; National Research Council 2011). Local tsunami sources, such as the Cascadia subduction zone, which includes Del Norte and Humboldt counties in northern California, could create a series of large surges that inundate coastal communities in these counties only minutes after initial ground shaking (Uslu et al. 2007; Cascadia Region Earthquake Workgroup 2013; Geist 2005) and therefore represent significant threats to life safety. Because of the wide array of tsunami sources, delineating or communicating a single tsunami hazard zone is difficult, not only for California but for many coastal communities throughout the world.

Recognizing the variety of tsunamigenic sources that threaten the California coastline, the California Geological Survey (CGS) and the California Governor's Office of Emergency Services (Cal OES) are working with some coastal communities to develop evacuation playbooks that include multiple evacuation zones (referred to as phases) based on tsunami scenarios of varying inundation potential and arrival times (Wilson and Miller 2014). The tsunami playbook approach provides options for evacuation planning so that emergency planners may tailor tsunami response activities to the size and location of the tsunami threat, thus improving capabilities and standardizing response activities for coastal emergency managers.

If a tsunami is triggered by a local or regional source with an expected arrival time of less than 4 h to reach the California coast, an evacuation of the maximum zone will likely be implemented to reduce confusion and limit delays in decision-making (Wilson and Miller 2014). Maximum-evacuation zones are based on cumulative inundation modeling efforts that incorporate a variety of far-field, local earthquake, and local landslide sources (Wilson et al. 2010) and field verification by geologists. Model results are then translated to evacuation zones based on discussions with local emergency planners for their specific jurisdictions. Maximum-evacuation zones were created for 35 separate regions covering all low-lying, populated areas along the California coast and do not represent potential inundation along the entire coastline. Descriptions of each tsunami source such as the length, width, depth, slip, and magnitudes for earthquake scenarios that were used as the basis for the maximum-evacuation zone can be found in Wilson et al. (2010).

If the expected wave arrival time for a distant tsunami is more than 4 h after initial ground shaking, a series of secondary playbook evacuation zones may be implemented. Wave arrivals of more than 4 h would provide emergency managers with the ability to recognize specific threats along the California coast and then communicate the appropriate evacuation zone for each jurisdiction (Wilson and Miller 2014). To help determine which evacuation zone to use, State and NOAA Weather Forecast offices will calculate expected tsunami flood elevations based on forecasted wave heights, existing ocean conditions, maximum tidal height during the first 5 h of the tsunami, forecasted error potential, and site-amplified run-up potential (Wilson and Miller 2014). The State and NOAA representatives use these predicted water elevation values to select and recommend the appropriate tsunami playbook evacuation zone for each community. These results are sent to all the communities in real time and are recommended as a minimum-evacuation zone for response and evacuation.

3 Methods

Our analysis estimates the community disruption and business costs of evacuating the portion of the California maximum tsunami-evacuation zone that is not in a scenario-evacuation zone. For the purposes of this analysis, we consider this to be an area of potential over-evacuation; however, without secondary evacuation plans available, emergency managers would not have the luxury of knowing the extent of inundation before a wave arrives and it can only be considered an over-evacuation in hindsight. In this section, we describe the tsunami scenario, variables, data, and methods we use in our analysis to estimate the number of displaced populations, sheltering costs, businesses with evacuation challenges, and the economic output, labor income, and employment for businesses in the area of potential over-evacuation.

3.1 Scenario tsunami-evacuation zones

Although the California coast is threatened by local and regional tsunami sources, our analysis must be based on a distant tsunami scenario with wave arrivals greater than 4 h if playbook evacuation zones are to be recommended to local emergency managers (Wilson and Miller 2014). The distant tsunami scenario used in this study is based on an M_w 9.0 megathrust earthquake west of Chile (hypocenter at 24°S latitude and 71°W longitude) at a depth of approximately 10 km at the interface of the subducting Nazca Plate and the overriding South American Plate. This scenario and related geospatial data summarizing playbook evacuation zones were developed originally as a collaboration between the CGS and Cal OES to support a statewide tsunami exercise on March 23, 2016 (State of California 2016). The scenario earthquake and subsequent tsunami is considered a plausible event for statewide evacuation planning, given the significant damage to California ports and harbors caused by tsunamis associated with Chilean earthquakes in 1960 (M_w 9.5) and in 2010 (M_w 8.8), as well as the 2014 M_w 8.2 Iquique earthquake and 2015 M_w 8.3 Illapel earthquake that caused local tsunamis in Chile but no evacuations or damage in California.

Significant wave activity along the California coast related to this tsunami scenario is estimated to begin approximately 12.5 h after the initial earthquake in Chile with official tsunami Warnings to coastal communities beginning approximately 1.5 h after the earthquake (Table 1; State of California 2016). Tsunami Warnings would be downgraded to an Advisory for the coastline from the Mexico border to Point Conception (Santa Barbara County) approximately 21.5 h after the earthquake and for the remainder of the coast 6 h later. The tsunami Advisory in California would be canceled approximately 36.5 h after the earthquake.

Table 1 Estimated chronology of a Chilean tsunami scenario developed for a 2016 California tsunami exercise (summarized from State of California 2016)

Time (h:min)	Tsunami alert status	Information
0:00	None	Earthquake occurs
0:05	Information Statement	Preliminary information is provided on earthquake magnitude (M_w 9.0), location (hypocenter west of Chile at 24°S and 71°W), and depth (10 km at the interface of the subducting Nazca Plate and the overriding South American Plate)
0:30	Watch	Tsunami alert level changes from an Information Statement to a Watch. Arrival times are estimated based on historical information. Information is gathered on tides and storm conditions
1:30	Warning	Alert is changed from a Watch to a Warning. Arrival times are given for San Diego (12:30), San Pedro (13:00), San Francisco (13:45), and Crescent City (14:30)
3:30	Warning	State and NOAA take forecasted amplitude (wave height) information from the National Tsunami Warning Center and use it in forecast tsunami elevation calculations
4:00	Warning	Predicted water elevations and evacuation zone recommendations are sent to county emergency managers
12:30	Warning	First waves arrive in southern California
21:30	Warning and Advisory	Tsunami Warning is downgraded to Tsunami Advisory from Mexico border to Point Conception (Santa Barbara County), but remains in effect for the rest of the California coast
27:30	Advisory	Tsunami Warning is downgraded for the rest of California. All of California coast is now under Tsunami Advisory
36:30	Advisory canceled	Tsunami Advisory is canceled for the entire California coast as water levels recede below 0.3 m at tide gauges

Based on the hypothetical chronology of tsunami alerts (Table 1), we estimate community disruptions and business costs for 0.5-, 1-, and 1.5-day evacuations. The hypothetical chronology of events (Table 1) suggests 36 h transpires between the initial earthquake and the cancelation of a tsunami Advisory, which serves as the basis for our evacuation estimates for 1.5 days. Although the Advisory level would not in itself require evacuations, we assume communities could extend evacuations from the tsunami Warning until areas are evaluated and determined safe for people to return. A potential one-day evacuation is based on the 24 h that transpires between State and NOAA offices communicating predicted water elevations and recommended evacuation zones at 4:00 h after the earthquake and the downgrade of the entire California coast to a tsunami Advisory at 27:30 h after the earthquake. Finally, a half-work-day evacuation (assumed to be 4 h in duration) is unlikely given the chronology of tsunami alerts, but is included to recognize the potential for an alert occurring in the afternoon, i.e., some businesses may experience half of a work day before closing early for an evacuation and then reopening the following morning after the Advisory is canceled. The half-work-day evacuation may also be considered from the perspective of potential future savings as monitoring and communication technology continues to improve, allowing for shorter disruptions.

The evacuation extent in each coastal community for the scenario tsunami is based on recommended evacuation playbook zones developed for the 2016 statewide tsunami exercise using the Chilean scenario (State of California 2016). These minimum-evacuation zone recommendations were based on calculated tsunami water elevations using the FASTER analytical approach as summarized in Wilson and Miller (2014). During an actual tsunami, FASTER values are calculated based on real-time tsunami forecast amplitudes (wave heights), storm and tidal conditions, potential tsunami forecast errors, and site-specific tsunami run-up potential on land. These variables are added together to provide an estimated maximum tsunami water elevation for each coastal location, and this flood elevation is then used by CGS and Cal OES to suggest a minimum-evacuation playbook phase to coastal emergency managers. The expected water elevations for the Chilean scenario were based on the following FASTER component assumptions (Fig. 2):

- *Tsunami forecast amplitudes* represent the expected near-shore tsunami wave heights above existing tidal and ocean conditions and are provided during an event by the National Tsunami Warning Center (NTWC) for preselected locations along the California coast. Tsunami amplitudes for this scenario were generated for the 2016 tsunami exercise (State of California 2016) and are within the range of numerical model results for scenarios from the Chile source region used for state tsunami inundation maps (Wilson et al. 2008; Barberopoulou et al. 2009). Scenario tsunami forecast amplitudes ranged from 0.4 m within San Francisco Bay in Alameda and Santa Clara counties to 2.1 m for Del Norte County (Fig. 2).
- *Storm and other existing surf conditions* are characterized during a tsunami from modeling performed by four NOAA National Weather Service Warning Forecast Offices, which cover all sections of coastline in California. We assume there is no significant storm activity for this scenario so the storm variable was given a zero value.
- *Existing tidal conditions* are obtained from tidal prediction curves for tide gauges (National Ocean Service 2016). The maximum tidal conditions for this scenario were assumed to be stable at −0.1 m statewide.
- *Potential errors in the forecast amplitudes* are assumed to be +30% of the forecast amplitude based on a comparison of forecasted amplitudes and measured and observed tsunami amplitudes in California during the 2010 Chilean–2011 Tohoku tsunamis

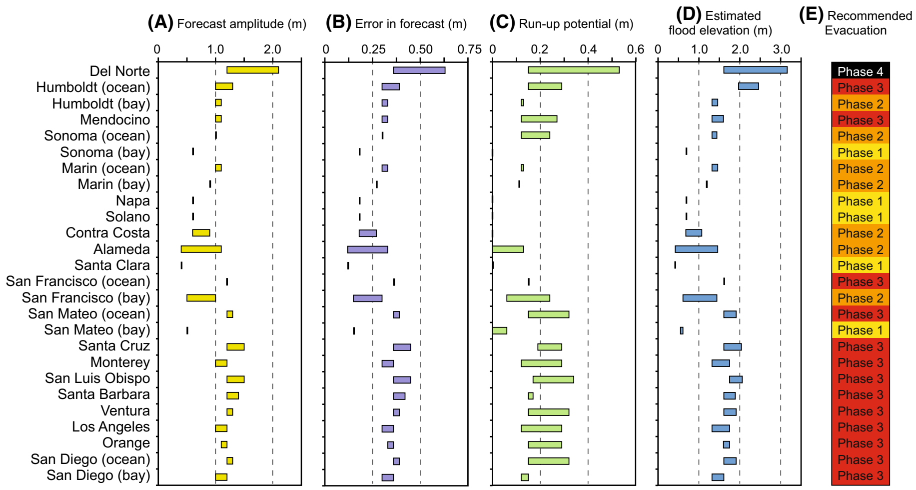

Fig. 2 Range of county-level assumptions, in meters (m) for **a** forecast amplitudes, **b** errors in forecast, and **c** run-up potential, **d** subsequent estimated tsunami flood elevations based on these assumptions, and **e** recommended evacuation phases for the Chilean tsunami scenario (summarized from State of California 2016). Additional assumptions to estimate flood elevations include no storm surge and a consistent tidal height of −0.10 m along the entire California coast

(Wilson et al. 2013), which corresponds to calculations by Whitmore (2003) from other events. Error values range from 0.12 m in San Francisco Bay (e.g., Santa Clara County) to 0.63 m in Del Norte County (Fig. 2)

- *Site-specific tsunami run-up potential* exists because of differences in bathymetric and topographic conditions at each location and is determined by the existing set of numerical model results for the state inundation maps (Wilson et al. 2008). Run-up factors range from zero to 30% and are multiplied by the near-shore forecast tsunami amplitude to provide the tsunami run-up height for each coastal location, ranging from 0 m in the San Francisco Bay to 0.53 m in Crescent City in Del Norte County (Fig. 2).

Based on these assumptions, tsunami flood elevations for the Chilean scenario range from 0.42 m in Alameda and Santa Clara counties to 3.16 m in Del Norte County, resulting in evacuation recommendations from phase 1 to phase 4 for California coastal counties (Fig. 1). Evacuation zones corresponding to each recommended phase were created for the majority of coastal communities as part of the statewide tsunami exercise (State of California 2016). Exceptions include the Sonoma, Napa, Solano, San Mateo, and Santa Clara coastlines along San Francisco Bay, because the recommended evacuation phase 1 for these locations in the scenario does not provide an actual polygon zone and instead simply recommends the evacuation of beaches, harbor docks, and piers (Wilson and Miller 2014). The development of playbook zones is an ongoing effort by CGS and has not been created yet for the counties of Mendocino (phase 3), Santa Barbara (phase 3), Contra Costa (phase 2), and the open-ocean coasts of San Mateo (phase 3) and Sonoma (phase 2). For these counties, we used 2009 maximum-inundation zones (Wilson et al. 2010) to delineate the scenario- and maximum-evacuation zones because that will be the basis for evacuation decision-making in these areas until playbook zones are developed.

3.2 Number of displaced populations

For this study of community impacts related to potential tsunami over-evacuations, we focus on the 97 incorporated cities and 20 counties along the California coast that have land in the maximum tsunami-evacuation zone (Fig. 1). Jurisdictions were delineated by census-designated place boundaries (U.S. Census Bureau 2010). Any residents or businesses located in unincorporated communities were aggregated and reported collectively at the county level as the "remaining land" of a specific county.

We estimate the number of residents in the area of potential over-evacuation by overlaying geospatial data representing the scenario and maximum tsunami-evacuation zones, jurisdictions, and block-level population counts compiled for the 2010 census (U.S. Census Bureau 2012). The number and types of employees in this area are similarly calculated using spatially referenced employment data in the 2012 Infogroup Employer Database (Infogroup 2012). Our business counts serve as approximations because we were unable to field-verify the latitude and longitude coordinates for each of the 1,014,765 businesses within the 20 counties of the study area. Types of businesses were identified using the North American Industry Classification System (NAICS) codes (U.S. Census Bureau 2007) associated with each business.

In addition to gauging the total number of employees that would evacuate, we also identify businesses or organizations that may have unique evacuation challenges for their on-site populations, such as correctional institutions, medical centers, adult residential care facilities, child day care facilities, and K-12 schools. All businesses will have some level of difficulty evacuating employees and customers. However, certain businesses and organizations will have particular difficulties, given the nature of the on-site populations and customers. Additional evacuation challenges will exist for those considered to have "at-risk populations," which are defined as individuals who may have additional functional needs related to communication, medical care, maintaining independence, supervision, or transportation. These functional needs may make it more difficult to evacuate the inundation zone in a timely manner. At-risk populations include children, senior citizens, and pregnant women, as well as individuals who have disabilities, live in institutional settings, are from diverse cultures, have limited English proficiency, lack transportation options, have chronic medical disorders, or have pharmacological dependencies. These populations will warrant additional evacuation time and unique response and relief procedures (U.S. Department of Health and Human Services 2012).

3.3 Evacuation costs

Evacuations will lead residents to find shelter, either in the short-term prior to first wave arrival or possibly overnight. Some residents may have friends and family to help them, whereas others may have the financial resources to afford temporary lodging. Some people, however, may need to rely on publicly provided shelters during the evacuation. Our half-day scenario is for individuals who come to the shelter during the evacuation warning, but return to their homes later that same day. The 1.5-day scenario describes individuals who remain at the shelter overnight and return to their homes the following morning. We do not calculate evacuation costs for a 1-day evacuation and consider it to be similar to the 1.5-day evacuation because of the likelihood of shelters being opened and the overall timing of the hypothetical event (Table 1).

To gauge the potential public sheltering demand, we used 2010 US Census population counts (U.S. Census Bureau 2012) and equations contained in the Hazus-MH 2.1 flood loss estimation methodology (Federal Emergency Management Agency 2013), in which shelter demand is based on the magnitude of the displaced population and then modified by their income levels and age distributions. Individuals with lower incomes will be more likely to use publicly provided shelters. Age also plays a role, where younger, less established families and elderly families will be more likely to use shelters. Analysis was completed with population count and age distribution data available at the census block level. Income distributions are available for census block groups; therefore, income distribution values were assigned to each block based on the larger block group value. Because of the small area likely to be affected, estimating sheltering needs at the census block was considered more accurate than the block group.

Once we estimated the demand for public shelters, we calculated the costs associated with operating them (e.g., food, facilities). Operating costs for shelters in the past are not consistent across locations nor are they well documented in the literature. A 2012 emergency planning guide from Massachusetts outlined financial planning for emergency events (Western Region Homeland Security Advisory Council 2012) and estimated a cost of approximately \$32.09 per person, per day (adjusted for 2016 inflation and cost of living differences between Massachusetts and California) based on past costs of shelter operations used by the local American Red Cross (ARC) Chapter. This estimate includes costs for food (\$19.25), dormitory and comfort supplies (\$3.85), electricity and heating (\$3.85), cleaning and sanitation (\$2.57), and miscellaneous costs (\$2.57). To provide regional context, we contacted regional emergency service managers and providers, such as West Coast representatives of the American Red Cross (ARC) and the Federal Emergency Management Agency (FEMA). The ARC Pacific Division estimates the cost to range between \$53 and 63 per person per day, which includes a blanket (\$5), a comfort kit (\$3), non-perishable service items (\$12), and either a cot (\$33) or a medical cot (\$43). The ARC also reports that their costs of providing food and shelter can include the cost of renting physical space and facilities. These costs vary widely, from zero to significant, depending on the location and event (Denise Everhart, Division Disaster State Relations Director, ARC Pacific Division). Another estimate of public shelter and evacuation costs are the donation requests made by the ARC to the general public, which state that \$50 provides a full day of meals and shelter for one person. However, FEMA staff reported that food and shelter costs can run as high as \$200 per person per night, depending on facilities and staff needs (Teri Giles, Emergency Management Program Specialist, FEMA Region X). Because of the range in sheltering cost estimates in the literature and in practice, we estimate costs using per person per day values of \$50 and \$200 in our analysis. We assume that public shelter providers could incur costs for evacuation scenarios that either last for one-half-day or 1.5 days. That is, once mobilized, service providers could incur per day costs even if evacuations last less than a full day and public shelters would not close in the middle of the night.

Many of the temporarily displaced populations will not seek out publicly available shelters and will find their own suitable arrangements. We estimate the number of people that will do this by subtracting the number of individuals seeking public shelter from the total number of displaced populations, again focusing only on the individuals in the maximum-evacuation zone that are not in the scenario zone. As was the case with public sheltering costs, we found little information on private evacuation costs, or costs incurred by individuals and families who do not use public shelter services. Whitehead (2003) estimated private evacuation spending from a survey of North Carolina residents following Hurricane Bonnie in 1998. Although this study is the most comprehensive look at private spending in response to an evacuation that we found, the results have limitations. The survey results do not specify the length of the evacuation or the average household size surveyed. A supplemental review of data from Hurricane Bonnie shows that shelters were active between one and three days, with the majority of shelter users and evacuees spending two days away from home (Post, Buckley, Schuh & Jernigan, Inc. 1999). Based on these findings, we assume that households that sheltered in hotels incurred daily costs of $195.18, including lodging costs of $115.60, food costs of $66.80, and other expenses of $12.78 (adjusted for cost of living and inflation). These costs apply to those staying in hotels or motels; however, individuals staying with friends or family likely would not incur lodging costs. Whitehead (2003) estimated that households using public shelters typically spent $61 per day for food ($44) and for miscellaneous items ($17).

Our analysis provides some indication of evacuation costs, but should not be interpreted as exhaustive due to several limitations. The first limitation is that the analysis does not estimate net effects on a regional scale to account for spending somewhere that would have happened otherwise in the evacuation zones. From a regional perspective, such an effect would count as a transfer of spending from one region to another rather than as a cost increase. For example, evacuees who planned on eating at a restaurant in the evacuation zone, but instead ate at a restaurant out of the zone, likely had no increased food expense. Conversely, evacuees who purchased groceries and planned on eating at home, but ate at a restaurant out of the evacuation zone, likely did pay more for food than they would have without the tsunami. A second limitation of this study is that we do not include travel costs for evacuees. For evacuees with vehicles, evacuating the tsunami zones typically would not involve traveling long distances. For this reason, we expect minimal travel costs. These costs, however, would not be zero. There will also be public transportation costs for evacuees without access to vehicles. A third limitation is that we assume that employees and tourists in evacuation zones would not use publicly provided shelters and would simply leave the area during an evacuation. For these reasons, our analysis of evacuation costs may underestimate the true evacuation costs.

There is also the potential that some aspects of evacuation costs may be overestimated due to the lack of data on how many evacuees not seeking publicly provided shelters may seek arrangements other than hotels. Limited studies from the evacuation literature for other hazards suggest a range of percentages. In two hurricane-related studies along the US Eastern Seaboard, the percentage of evacuees seeking shelter with friends or families ranged from 41% (Cutter et al. 2011) to 71% (Whitehead 2003). In a study of local evacuations for a 1998 flood in Texas, approximately 41% of evacuees went to friends and family (Mayunga 2012). Hurricane- and flooding-related evacuation studies in other parts of the USA provide some insight on potential costs, but may not directly relate given the differences in evacuation decision-making for tsunamis (approximately 11 h between tsunami warning and wave arrival for the Chilean scenario) compared to hurricanes (typically measured in days). In addition, potential socioeconomic and cultural differences between our study area and areas summarized in past work could influence the degree to which people seek hotels or accommodations with friends and family. Estimated private evacuations costs therefore should be considered approximations, given the potential for under- and over-estimation of various elements.

3.4 Short-term business impacts

Short-term impacts to businesses in the area of potential over-evacuation were estimated by combining the employment data from the 2012 Infogroup Employer Database with

2014 county-level Impact M for Planning (IMPLAN) data on annual economic output and labor income, which is based on input-out analyses that include regionally specific transaction descriptions (IMPLAN Group 2015). A price adjustor of 1.00275 was used to convert 2014 dollars to 2016 dollars based on the Consumer Price Index (U.S. Department of Labor Bureau of Labor Statistics 2016). Total county economic output and labor income were divided by the number of employees in the county and organized by two-digit NAICS code. We then multiplied these data by the number of employees in the area of potential over-evacuation to approximate the annual economic output, labor income, and lost employment costs, by economic sector. Our method assumes that the relationships between employment and economic output and labor income by NAICS code at the county level approximate the relationships at the sub-county areas of our analysis.

To gauge the short-term business impacts during the tsunami evacuation, we converted annual economic output, labor income, and lost employment estimate to daily or work day measures of these variables. To do this, we created a table of "disruption coefficients" by NAICS code that approximates the percentage of economic activity that we assume would stop during an evacuation. For example, we assume that manufacturing processes and retail would stop 100% during an evacuation because all employees would be evacuated and off-site production or merchandise sales are not possible. We assumed disruption coefficients of 50% for financial transactions and 75% for utilities and shipping because of the possibility that a portion of these sectors would continue operating during an evacuation, for example a broker being able to work from home during an evacuation or ships and trucks already in transit.

Converting from annual to daily measures of our economic variables required that we divide the annual measures by the number of work days in a year, by NAICS code. We made assumptions regarding sectors that work seven days per week versus those that typically work five days per week. For example, we assumed that telecommunications, retail sales, and entertainment sectors operate seven days per week, while banking, professional services, and wholesale trades operate five days per week. Finally, we estimated the output, income, and employment impacts of the evacuation scenarios by dividing the annual values for these variables by the number of work days per year. We then multiplied this value by the disruption coefficient and then by the duration of the evacuation scenario.

Our analysis of economic output, labor income, and employment focused on businesses directly affected by the evacuations. We did not include multiplier effects, or how direct impacts ripple through an economy. For example, we did not include costs to firms that supply goods and services to restaurants that were shut down by the evacuation. We excluded multiplier effects in large part because of the relatively short duration of the evacuation scenarios (4 to 36 h), and the challenges of distinguishing between lost sales (which we would count as an evacuation cost) from delayed sales (which we would not include in evacuation costs). By excluding multiplier effects, our analysis likely underestimates the true amount of evacuation costs.

4 Results

4.1 Number of residents and sheltering costs

Of the 97 incorporated communities and 20 counties with land in the maximum-evacuation zone, geospatial analysis of population and hazard data suggests that only 72 of the

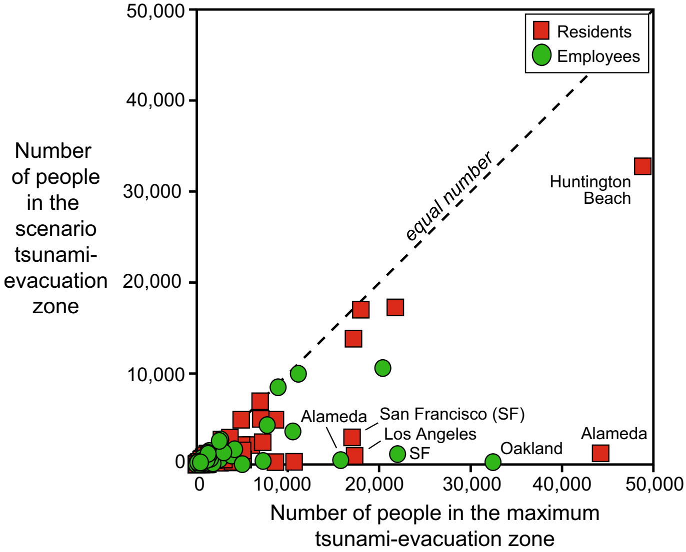

Fig. 3 Number of residents and employees by community in the California maximum tsunami-evacuation zone compared to the number of residents and employees in a tsunami-evacuation zone associated with the Chilean tsunami scenario

communities and 18 of the counties have residents and businesses in the playbook evacuation zones associated with the Chilean tsunami scenario (Fig. 1). Eleven other communities have residents and businesses only in the maximum-evacuation zone, but not in the scenario zones (noted with asterisks in Fig. 1). Fourteen communities and unincorporated land in one county (Santa Clara County) have land in evacuation zones, but no estimated residents or businesses in these areas (noted with open circles in Fig. 1).

We estimate that there are 322,570 residents in the maximum tsunami-evacuation zone but only 143,925 in Chilean scenario-evacuation zones for California, suggesting that 178,646 residents (55% of total) may be evacuating areas not likely to be inundated from this specific scenario. Approximately 60% of the residents in the maximum zone but not the scenario zone are in Alameda County (62,245 residents, 35% of total residents in the maximum zone), Los Angeles County (27,559 residents, 15% of total), and Orange County (17,723 residents, 10% of total). At the community level, the greatest numbers of residents in this area are in Alameda (43,021), Los Angeles (16,367), Huntington Beach (16,067), San Francisco (14,033), and Oakland (10,389) (Fig. 3). Some communities only have estimated populations in the maximum-evacuation zone and not the scenario-based zones (e.g., East Palo Alto, Vallejo, Redwood City, and Pacific Grove) and others have no estimated populations or businesses in either zone (e.g., Fremont, Mountain View, Sand City, El Segundo, and Westminster), indicating that a scenario-based evacuation may still result in evacuations of individuals on beaches and docks, but not widespread evacuation of homes or businesses in these communities.

With regard to public shelter demand, we estimate 16,522 residents of the 29,658 residents likely to seek publicly provided shelters during the scenario tsunami are in the area of potential over-evacuations (Fig. 4). This number reflects 56% of the residents in the maximum tsunami-evacuation zone that may seek public shelters. The greatest numbers of residents from this area that may seek public shelters are in Alameda (5571), Los Angeles

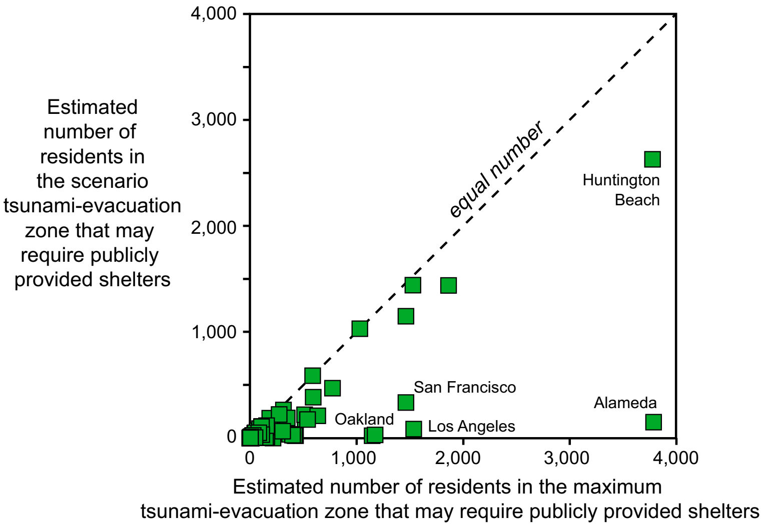

Fig. 4 Number of residents by community in the California maximum tsunami-evacuation zone that may require publicly provided shelters compared to the number of residents in a tsunami-evacuation zone associated with the Chilean tsunami scenario that may also require publicly provided shelters

(2440), Santa Cruz (1565), and Orange counties (1296), which collectively account for 66% of the shelter demand for individuals in this area. At the community level, the greatest numbers of residents in this area that may seek public shelters are in Alameda (3637), Los Angeles (1450), and Huntington Beach (1147) (Fig. 4).

Costs associated with the public sheltering of the 16,522 residents in the area of potential over-evacuation range from $413,050 (assuming a half-work-day evacuation at $50 per day) to $1.24 million (assuming a day and a half at the same rate). Assuming the higher rate of $200 per day, public shelter costs for individuals in this area rise to $1.65 million and $4.96 million (half-day and 1.5 days, respectively). As discussed earlier, the assumption of a 1.5-day use of shelters is possible, given the chronology of warning messages (Table 1) and because organizations operating shelters will likely plan for individuals staying overnight and would not recoup expenses if people leave early. Some individuals also may choose to stay at the shelters overnight if there is an uncertainty in the wave forecasts. The greatest expenditures to operate public shelters for 1.5 days for residents in the area of potential over-evacuation are in Alameda County ($417,837) and Los Angeles County ($182,965), assuming a $50 per day, per person rate (Fig. 5a).

Of the 178,646 residents in the area of potential over-evacuation, we estimate 91% (162,124) of them will not seek out public shelters during the evacuation for the scenario tsunami based on age and income distributions. The high percentage of residents not seeking public shelters is likely a reflection of the typically higher incomes for households along the California coast. We found no reliable data on the portion of evacuees who stay with family versus in hotels or motels; therefore, for illustrative purposes, we assume that all individuals who do not use public shelters pay for accommodations and food. Based on the US Census Bureau estimate of 2.94 individuals per household in California, there are approximately 55,144 households in the area of potential over-evacuation, with results in a range from $2.2 million in private sheltering costs for a half-work-day evacuation to $13.0 million for a 1.5-day evacuation. As was the case with public sheltering costs, the highest

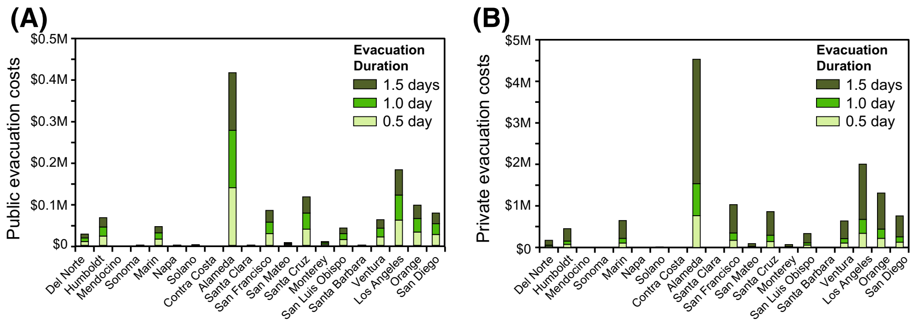

Fig. 5 Cumulative sheltering costs from 0.5 to 1.5 days for **a** public shelters and **b** private evacuations, by county, for individuals in the area of potential over-evacuation

private expenditures would be in Alameda and Los Angeles counties ($4.5 million and $2.0 million, respectively, assuming a 1.5-day evacuation) (Fig. 5b).

4.2 Numbers and types of businesses

We estimate that there are 159,271 employees statewide in the area of potential over-evacuation, representing 71% of the total number of employees in the maximum-evacuation zone (223,040). Approximately 42% of the employees in the area of potential over-evacuation are in Alameda County, specifically the cities of Oakland and Alameda (32,215 and 15,355 employees, respectively) (Fig. 3).

Our analysis indicates that the area of potential over-evacuation contains 153 businesses with at-risk populations that will have particular mobility limitations and functional needs during an evacuation, including 4 correctional institutions, 7 medical centers (including clinics, surgical centers, treatment centers, and a dialysis center), 38 adult residential care centers, 44 child day care centers, and 60 primary or secondary schools (Fig. 6). Alameda County has the greatest number of these business types (74), including 3 of the 4 correctional institutions, 21 of the 44 child day care centers, 19 of the 38 adult residential care centers, and 26 of the 60 primary or secondary schools. Marin County contains the second highest number of these business types (20), largely due to 11 schools.

Another potential issue related to over-evacuations is if public safety offices are asked to evacuate, which may complicate efforts to coordinate and implement evacuations. Results suggest the area of potential over-evacuation contains 32 public safety offices, with most in Alameda County (10), followed by Los Angeles (6) and Del Norte (5) counties (Fig. 6). Public safety offices in the area of potential over-evacuation include 12 fire departments, 10 local police departments, 6 county sheriff offices, 2 US Coast Guard stations, 1 Civil Defense office, and 1 State Highway Patrol office.

4.3 Short-term business impacts

Evacuating businesses in the area of potential over-evacuation (i.e., that portion of the maximum zone not included in the scenario zone) for half-work-day results in approximately $40.8 million in lost economic output (of which $13.9 million is related to lost labor income) and the equivalent of 239 person-years of lost employment, which is a time

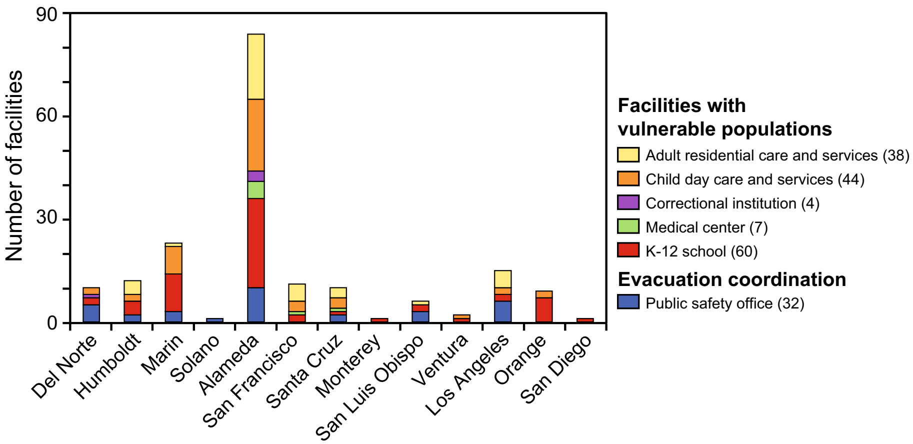

Fig. 6 Number of facilities, by county and by type, with evacuation challenges in the area of potential over-evacuation

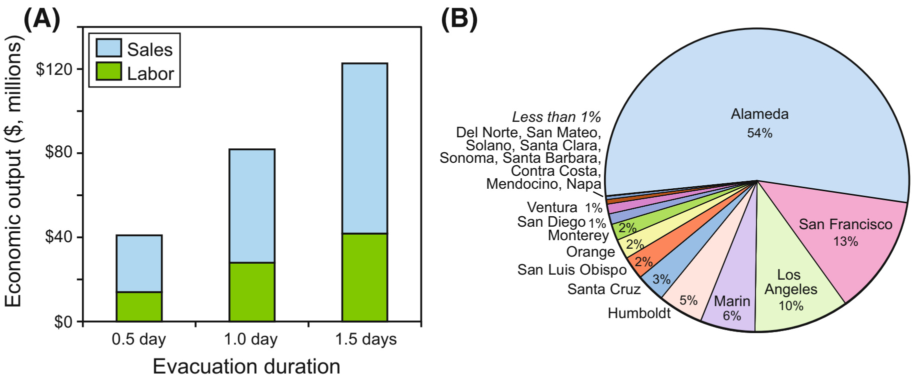

Fig. 7 Estimated lost economic output for businesses in the area of potential over-evacuation **a** for the entire California coast assuming multiple evacuation durations, and **b** as a percentage by county for an evacuation that lasts 1.5 days

unit used in industry for measuring work (Fig. 7a). This increases to $122.3 million in lost economic output ($41.7 million of which is labor income), and 717 lost person-years of employment if businesses were closed for 1.5 days. Approximately 54% of the lost economic output is related to business closures in Alameda County ($66.0 million), followed by 13% for businesses in San Francisco County ($15.6 million) and 10% in Los Angeles County ($12.4 million), with percentages in the remaining counties each less than 10% (Fig. 7b).

Lost economic output for businesses in the area of potential over-evacuation is highest in Alameda County ($66.0 million for 1.5-day evacuation), but it also represents 99% of the losses for that county in the maximum-evacuation zone for the same time period, suggesting that much of these losses could be avoided with a scenario-based evacuation (Fig. 8). The second highest amount of lost economic output is in San Francisco County ($15.6 million), and this estimate represents approximately 96% of the potential losses

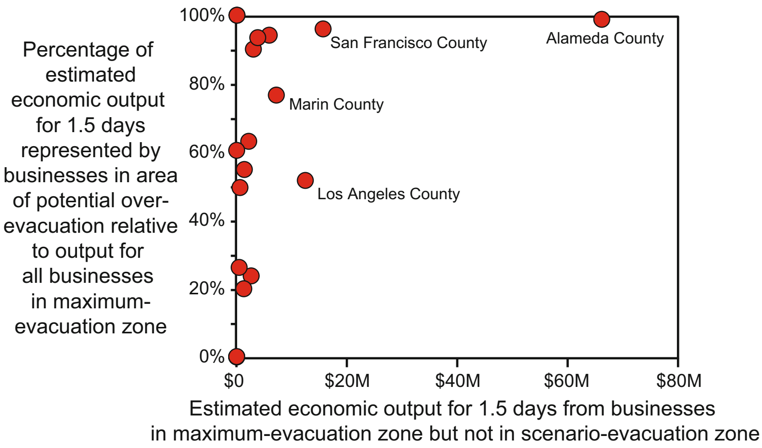

Fig. 8 Estimated lost economic output (assuming a 1.5-day evacuation) for businesses in the area of potential over-evacuation (by county) compared to the percentage of the economic output it represents relative to lost economic output for all businesses in the maximum tsunami-evacuation zone

associated with the maximum-evacuation zone. Although the total amounts are not as high as Alameda or San Francisco County, this observation is true for other counties, where losses in the area of potential over-evacuation represent a substantial percentage of the losses associated in the maximum-evacuation zone, including Santa Clara and Solano counties (each 100%), Humboldt County (94%), Santa Cruz County (93%), and San Luis Obispo County (90%). Statewide, economic losses in the area of potential over-evacuation represent 76% of the estimated losses of businesses in the maximum-evacuation zone.

With regard to business sectors most impacted by a potential over-evacuation (Fig. 9), 34% of the lost economic output is related to manufacturing-related businesses (i.e., NAICS codes 31-33), which is $41.6 million for a 1.5-day evacuation. A second group of business sectors with similar percentages (each approximately 7%) include professional, scientific, and technical services; information; real estate and rental services; accommodation and food services; and retail trade. The remaining business sectors each represent less than 5% of the potential lost economic output in the area of over-evacuation.

5 Discussion

Developing effective evacuation procedures and policies are critical to saving lives from tsunamis. Although evacuation procedures are primarily designed for minimizing loss of life, the costs of evacuations are worth considering as well, given continual improvements in tsunami monitoring and communications technology. To support ongoing discussions on the use of scenarios to guide evacuations, we examined the implications of evacuation policies in California based on a maximum zone versus a specific scenario zone. We focus on the area of land in the maximum-evacuation zone that is not in the scenario-evacuation zone and estimate the number of residents and employees, the types of businesses with unique evacuation challenges, sheltering costs, and short-term business impacts. In this section, we discuss the implications of our results on evacuation planning, not only in California but also in coastal communities nationally and throughout the world.

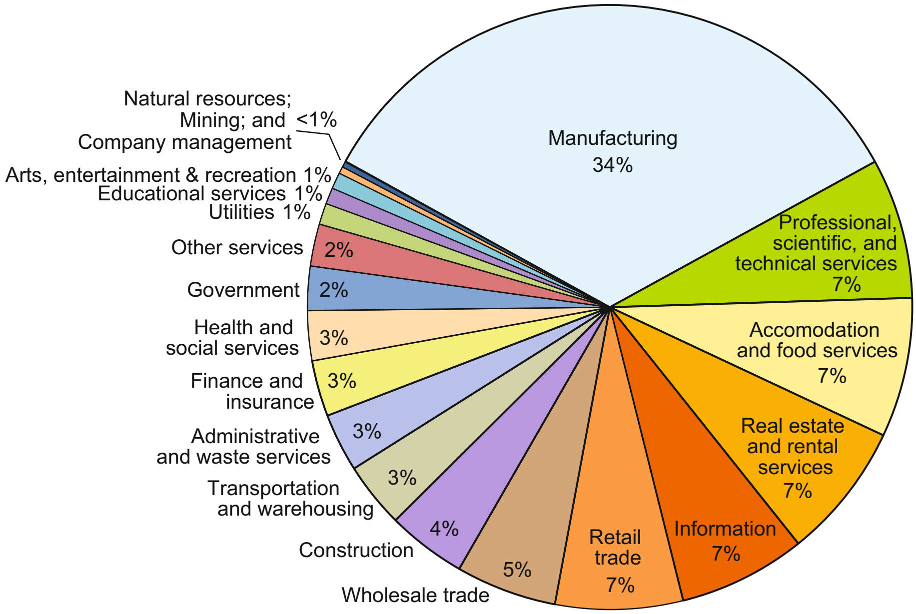

Fig. 9 Estimated lost economic output, by business sector (based on NAICS code), for businesses in the area of potential over-evacuation, assuming an evacuation of 1.5 days

5.1 Implications for evacuation planning

Our analysis indicates that there are a substantial number of residents (178,646) and employees (159,271) in the California maximum tsunami-evacuation zone that may not be directly affected from tsunami waves associated with a Chilean earthquake scenario. These individuals represent 55% of the residents and 71% of the employees in the maximum tsunami-evacuation zone, suggesting that the use of scenario-based evacuations in California could greatly reduce the number of people that would be encouraged to evacuate. This reduction in evacuees would also minimize burdens and congestion on transportation networks during an evacuation, which may allow individuals truly at risk from imminent waves to have quicker access to safe areas. For this one scenario, such a decision would dramatically reduce the number of evacuees in certain counties, such as Alameda, Los Angeles, and Orange, which collectively represent 60% of the residents in the area between the scenario and maximum-evacuation zones. Although evident for the specific Chilean earthquake scenario used in this case study, this concentration of people may not be the case if other scenarios were compared, such as tsunamigenic earthquakes originating in Japan or Alaska.

Evacuation cost estimates suggest that private expenditures would be greater than expenditures for operating publicly provided shelters. Lost public expenditures to shelter 16,522 people from the area of potential over-evacuation are estimated to range from \$0.41 to \$1.2 million (0.5- and 1.5-day evacuations, respectively), whereas private expenditures range from \$2.2 million to \$13.0 million (0.5- and 1.5-day evacuations, respectively) for the other 162,124 residents in this area that may seek out their own arrangements during the evacuation. Approximately 56% of the residents in the maximum-evacuation zone seeking publicly provided shelters are in the area of potential over-evacuation, again suggesting the benefit of using scenarios to guide evacuation decisions. The majority of these individuals are in Alameda, Los Angeles, Santa Cruz, and Orange counties, suggesting that the benefits of scenario-based evacuations are not equal across a region for this specific scenario and that certain jurisdictions may have more to gain than others. As noted earlier, it is unclear how many evacuees seeking private shelter may use hotels versus staying with friends and family; therefore, private evacuation costs should be interpreted as approximations.

Estimates of disruption costs for businesses in the area of potential over-evacuation range from $40.8 million for a 0.5-day evacuation up to $122.3 million for a 1.5-day evacuation, with 54% of these disruption costs located in Alameda County (Fig. 7). In several counties (including Alameda), these costs comprise significant components of potential disruptions for all businesses in the maximum-evacuation zone (Fig. 8), suggesting that implementing a scenario-based evacuation plan may substantially reduce business disruption costs. Based on the types of businesses in the area of potential over-evacuation (Fig. 9), some of these disruption costs may be recouped over time (e.g., 34% are associated with manufacturing) or are less than estimated because of the ability of some businesses to continue to operate during an evacuation. For example, 3% of employees in the area of potential over-evacuation are associated with finance and insurance sectors, which may have the ability to work completely off-site. Therefore, our estimate of $122.3 million for a 1.5-day evacuation may be high, given these contextual issues related to business type.

The substantial number of people, sheltering costs, and business disruption costs in the area of potential over-evacuation may suggest quick support for scenario-based evacuation zones in all future tsunamis. However, there are several areas for additional and continued discussion that provide context on the complexity of evacuation decision-making. First, evacuation procedures based on scenarios require a wide array of scenarios to be developed and compiled in an easily accessible format, which is no small task. In California, this effort is currently underway in the form of scenario playbooks for each coastal jurisdiction (e.g., Wilson and Miller 2014). However, we are not aware of similar efforts in other coastal areas around the world.

Other issues that warrant discussion are the importance of (a) educating practitioners and (b) when to best inform the general public on scenario-based evacuations. Maximum-evacuation zones may be the foundation of pre-event tsunami outreach and awareness efforts, such as signs posted at beach access points and information for homeowners living in tsunami-prone areas. Therefore, because maximum-evacuation zones may be more readily recalled in their minds, practitioners and the general public may exhibit an availability bias (Tversky and Kahneman 1973) in their evacuation decision-making and continue to evacuate based on the maximum-evacuation zones (which in terms of public safety is generally appropriate). In addition to availability bias, varying risk tolerances of practitioners and evacuees may also result in people relying on maximum-evacuation zones. Individuals may interpret the uncertainty inherent in all hazard modeling and warnings and choose to evacuate maximum-evacuation zones. Recognizing the need for and then developing outreach efforts to minimize availability bias and varying risk tolerances of both evacuees and public officials may help reduce the likelihood of shadow evacuations, defined as individuals who choose due to different risk perceptions to evacuate an area that is larger than specifically recommended by public officials (Zeigler et al. 1981; Dash and Gladwin 2007; Gladwin et al. 2001).

One area where scenario-based evacuations may have the greatest benefit is in evacuation decision-making and prioritization for businesses and organizations containing individuals with limited mobility, access and functional needs, or other evacuation challenges. In our case study, there are many correctional institutions, medical centers, adult residential care centers, child day care centers, and schools in the area of potential over-evacuation (Fig. 6). In each case, evacuations are not simply asking at-risk individuals to independently move to high ground. Each of these facilities could have substantial evacuation challenges, such as how to move inmates from a correctional facility, to arrange school buses for K-12 students, and to move intensive care or dialysis patients. For school evacuations, there may not be enough buses to transport all at-risk individuals at the schools, resulting in parents being asked to retrieve their children and additional stress to the transportation network.

Evacuating hospitals and other medical centers is a complex decision that cannot be taken lightly. The time needed to complete an evacuation is highly dependent on the level of coordination, the availability of appropriate transportation, and the availability of qualified personnel for transferring patients. Coordination during evacuations is critical to ensure that no single facility is overloaded with transfer patients, as well as for centralized tracking of patients so that family members can find them following the event. Transportation options may include buses or vans for those who are ambulatory, wheelchair-adaptable vans for some patients, and ambulances with basic or advanced life-support capacities for critical or intensive care patients. Without the proper level of onboard medical support, a patient's health is jeopardized. For example, 4 ventilator-dependent patients died during hospital evacuations during Tropical Storm Allison, and 2 additional patients died within 24 h (Rother 2001). In addition, some patients may not be able to be moved immediately, such as patients undergoing dialysis (typically a 3–5 h procedure) or undergoing surgery, either in a hospital or outpatient surgical center. Staffing during evacuations is a significant challenge because many patients cannot simply walk out of a building to safe areas. This is an issue at hospitals, where staff-to-patient ratios are not equal. It is also an issue at assisted living facilities and senior citizen complexes where residents have fewer health needs than those in hospitals, but facilities have fewer full-time staff on-site at any one time. Nursing facility residents are also at risk of not being able to evacuate in a timely manner because, although skilled nursing facilities are required to have an evacuation plan by regulation, many nursing facilities have not exercised those plans (Kuba et al. 2004).

Comprehensive hospital evacuations are very complex, time-intensive processes as well. For example, following the 1994 Northridge earthquake, one hospital felt that their patient population was in immediate danger from building damage, and they evacuated 334 patients, including intensive care patients, out of the building to an open area outside of the hospital in 2 h (Schultz et al. 2003). However, comprehensive evacuations that included moving patients to new facilities took between 9 and 19 h to complete for the 6 hospitals that completely evacuated their facilities following the same earthquake (Schultz et al. 2003). In a non-disaster environment, the University of California, Los Angeles, Medical Center transferred 350 patients from an old building to a new facility across the street in 8 h. This was accomplished by not admitting any new elective patients either the day before or the day of the transfer and by having a full staff at both facilities to maintain levels of care, ensure full functionality at both facilities, and provide additional transport staff (Groves 2008). Given the time constraints of wave arrival for our scenario earthquake (12 h after the initial earthquake), compressed evacuation procedures may need to be implemented for certain facilities, which ultimately may endanger the health of some of the patients. Therefore, determining whether or not an evacuation is needed (either horizontally to high ground or vertically to higher building floors) is a paramount decision for hospital administrators.

Recognizing these potential complications, typical clearance times, and necessary evacuation conditions, evacuations from the 153 businesses in our case study with at-risk populations that have limited mobility or functional needs will be not only challenging, but present a conundrum for site managers. On the one hand, managers may wish to delay an evacuation to determine whether it is truly needed and if so, could a small scenario-evacuation zone be used. On the other hand, they also must immediately initiate an evacuation if they are to maximize the number of people that they evacuate. This decision of competing issues highlights the importance of improving managers' ability to make tsunami-evacuation decisions. In addition, the managers of businesses and organizations with at-risk individuals may be very receptive to advances in evacuation procedures as tsunami monitoring, warning dissemination, and communication technology continue to improve.

5.2 Areas for future research

Given the lack of previous studies to evaluate the costs of potential over-evacuations, our analysis relies on a number of assumptions and simplifications. Research in several areas would help further the understanding of the social and economic costs of tsunami evacuations. Although not an exhaustive list, we discuss here three areas for continued research—evacuation clearance times for businesses, the issues of lost versus delayed costs, and refinement of private expenditures.

The first topic that warrants future research is improving our understanding of the typical occupancy rates and clearance times for businesses or organizations with unique evacuation challenges, such as adult residential care centers, schools, and medical centers (Fig. 6). This information would help gauge the amount of time a business or organization would have to make evacuation decisions. As discussed earlier, taking this additional time for making an evacuation decision may be critical for organizations where evacuations could be challenging to complete in the available hours before wave arrival. A related area for further research is the ability to vertically evacuate these individuals to higher floors, since horizontal evacuations to higher ground elsewhere may not be realistic.

One aspect of economic modeling that warrants further research relates to better understanding delayed versus lost economic output for businesses in the area of potential over-evacuation. For example, we assume in our case study that businesses in retail and accommodation sectors would be unable to recoup losses because of lost shopping opportunities. However, it is possible that a retail store could increase their hours of operation after an event to help offset the losses incurred during a tsunami warning. This is likely to be more realistic for manufacturing businesses, which may be able to increase production hours over subsequent weeks to compensate for lost hours during an evacuation. Studies on which business sectors may lose or simply delay economic output would help refine our development and use of disruption coefficients and could facilitate a multiplier analysis of how direct effects work their way through an economy.

Another area for further research relating to evacuation costs involves assumptions of private expenditures of evacuees. In our study, we did not account for travel costs (e.g., gas) for individuals leaving their homes and heading either to a public shelter or to other accommodations. These travel costs may be low, because shelters or hotels may only be a few miles from one's home or place of business. However, transportation studies that model how evacuations affect the routes and volume of traffic, and the associated increased travel costs, would provide valuable information on determining the total costs of a tsunami evacuation. A related aspect of evacuations is improving our understanding of where individuals go if they choose to not use public shelters. In the absence of data related to private costs associated with past tsunami evacuations, we assumed in our case study that all individuals that do not use public shelters would seek out commercial accommodations. However, many of these individuals may seek refuge from families or friends during a tsunami warning, which would greatly reduce our estimate of private expenditures. Limited research on hurricane evacuations suggests a significant number of evacuees stay with family or friends (Whitehead 2003; Cutter et al. 2011; Mayunga 2012). Therefore, additional research on private expenditures as they relate to tsunami evacuations, or any short-term evacuation, would greatly improve future estimates.

6 Conclusions

Tsunami playbooks provide secondary evacuation options which can allow for more accurate and consistent response plans for communities, as well as reduce the public exposure to under- and over-evacuations. This case study of community disruptions from tsunami evacuations focused on estimating the number of residents and employees, the types of businesses with unique evacuation challenges, sheltering costs, and short-term business impacts in the portion of a maximum-evacuation zone not in an area likely to be inundated for a specific scenario (e.g., a Chilean earthquake in our study). The analysis was not conducted to recommend an end to evacuation policies based on maximum zones but instead to introduce concepts for gauging the implications of various evacuation policies as agencies continue to discuss the substantial warning coordination, communication, outreach, and response planning aspects that would need to be addressed before scenarios are solely used as the basis for evacuations. Based on our analysis, we reach several conclusions that bear on future tsunami risk reduction research and application to at-risk communities.

- Scenario-based evacuations could greatly reduce the number of residents and employees that would be advised to evacuate (e.g., 178,646 residents and 159,271 employees based on a comparison of a maximum-evacuation zone and scenario-evacuation zones associated with this distant tsunami caused by a Chilean earthquake).
- The difference between resident/employee exposures for the maximum-evacuation zone versus those in the scenario-evacuation zone is not consistent across all jurisdictions and is primarily concentrated in three counties.
- Private evacuation spending is estimated to be greater than public expenditures for operating shelters ($13.0 million compared to $1.2 million for a 1.5-day evacuation), and the majority of private and public expenditures are in Alameda County.
- Business disruption costs for the areas between scenario and maximum-evacuation zones are approximately $122.3 million for a 1.5-day evacuation, with the highest amount of losses in Alameda County, but also related to manufacturing, suggesting that disruption costs may be recouped over time.
- There are many businesses and organizations that contain individuals with limited mobility or access and functional needs in the area of potential over-evacuation that will have substantial challenges if asked to evacuate.

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