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Population vulnerability of residents, employees, and cruise-ship passengers to tsunami hazards of islands in complex seismic regions: A case study of the U.S. Virgin Islands

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ABSTRACT

Reducing the potential for loss of life from tsunamis is challenging on islands located in complex seismic regions given the multiple sources that surround islands, differences among islands in the amount of time needed to evacuate before wave arrival, and the high number of residents, employees, and tourists in tsunami-hazard zones. We examine variations in population vulnerability in island communities to multiple tsunami threats and use the United States territory of the U.S. Virgin Islands (USVI), including St. Thomas Island, St. John Island, and St. Croix Island, as our case study. We estimate the tsunami-hazard exposure of residents, employees, and cruise-ship passengers on vessels docking at USVI maritime facilities, as well as model pedestrian travel times out of inundation zones for 13 credible tsunami scenarios. Results indicate that the threat to life safety in USVI posed by tsunamis is not equal among the three islands, both in terms of the magnitude of people in hazard zones and the amount of time available to evacuate for the various scenarios. The number of employees and cruise-ship passengers in tsunami-hazard zones is orders of magnitude higher than the number of residents, suggesting that risk assessments that only account for residents are under-estimating threats to life safety from tsunamis. Finally, reducing departure delays has a greater impact than increasing pedestrian travel speeds on reducing the number of people that may have insufficient time to evacuate hazard zones before wave arrival.

1. Introduction

Developing risk-reduction strategies to minimize loss of life from tsunamis requires an understanding of estimated wave-arrival times from potential tsunamigenic sources, the extent of population exposure and vulnerability to these threats, and options for reducing potential fatalities. Many research and outreach efforts to improve this understanding have focused on distinctions of “local” versus “distant” tsunamis that may strike low-lying coastal areas, with local events arriving within minutes or tens of minutes after local generation (e.g., by an earthquake, volcano, submarine landslide, or subaerial landslide) and distant events arriving hours after generation elsewhere. For example, tsunami hazard zones used for emergency planning in the U.S. States of Oregon and Washington are classified as either local events with waves that arrive within minutes after a Cascadia subduction zone earthquake or distant events with waves that arrive several hours after an Aleutian-Alaska subduction zone earthquake off the coast of Alaska [1].

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Although a local versus distant tsunami distinction may be appropriate for some coastal communities, it may be less helpful in island communities in complex seismic regions where they may be surrounded by multiple tsunamigenic sources. What may be considered a local event for one area of an island may be better communicated to the public as a distant event in other areas due to wide ranges in estimated wave-arrival times and distances to safety. Therefore, discussing types of tsunami threats and population vulnerability to these threats in island communities may require a more nuanced approach than simply labelling a specific source as local or distant. To date, the literature has largely focused on single tsunami scenarios or on simple distinctions of local or distant [1].

The United States (U.S.) territory of the U.S. Virgin Islands (USVI), comprised of St. Thomas, St. John, and St. Croix Islands, provides an opportunity to examine variations in population vulnerability to multiple tsunami sources in a complex seismic region (Fig. 1) that has experienced many significant earthquakes in the past several centuries [2,3]. The USVI are located on the Virgin Islands Shelf on the northeastern edge of the Caribbean tectonic plate. A subduction zone between the North American and Caribbean tectonic plates creates the Puerto Rico Trench, which is north of USVI and believed to be the source most capable in creating the largest tsunamigenic earthquakes in the region [4]. The Anegada Passage, which contains the St. Croix Basin and the Sombrero Basin, separates northern (St. Thomas and St. John Islands) and southern (St. Croix Island) USVI and contains several faults capable of generating tsunamis [5]. The 1867 M_w 7.2 earthquake and tsunami disaster [6–8] is believed to have occurred in this area [9,5], creating the largest tsunami run-up value ever recorded in the Caribbean (15.2 m in St. Thomas Island) and killing 24 people [10].

Another aspect of population vulnerability to tsunami threats that exists everywhere to some degree but may be heightened in island communities is the presence of non-residents in hazard zones. To date, previous studies on population vulnerability to tsunamis have focused on residential exposure (e.g., [12]), with less attention paid to employees, customers at businesses, and tourists in tsunami-hazard zones [13]. USVI provides an ideal case study for characterizing non-residential exposure and evacuation potential to tsunami threats given the importance of tourism to the territorial economy. Approximately 60 % of USVI's gross domestic product (GDP) and approximately 50 % of the total civilian employment is related to tourism, trade, and other services. There are an estimated

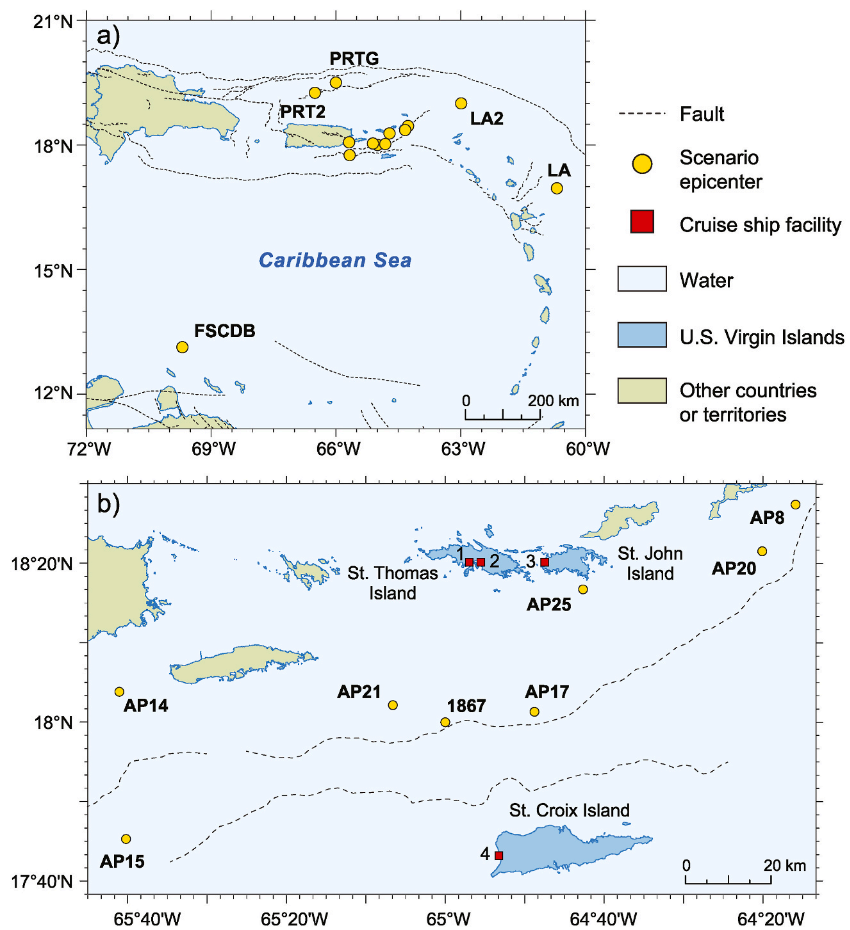

Fig. 1. Study area maps of the U.S. Virgin Islands and tsunamigenic seismic sources used in this study, including (a) a regional map of countries and territories surrounding the Caribbean Sea, and (b) a map focusing on the U.S. Virgin Islands. Tsunami scenario abbreviations are explained in Table 1. Generalized fault lines are from Styron and Pagani [11]. Maritime facilities that provide support to cruise ships in USVI are described in section 2.2 and are at Crown Bay, St. Thomas Island (#1); Havensight, St. Thomas Island (#2); Cruz Bay Harbor, St. John Island (#3); and Frederiksted, St. Croix Island (#4), as defined by Virgin Islands Port Authority (2024).

87,145 residents in USVI [14], yet the U.S. territory has approximately 3 million tourists per year, primarily from visiting cruise ships [15].

The objective of this paper is to examine population exposure and evacuation potential for multiple tsunami sources that threaten the coastal communities of the St. Thomas, St. Croix, and St. John Islands of the U.S. Virgin Islands (Fig. 1). Our approach builds on past efforts in the tsunami-evacuation literature in two ways. First, we include a range of tsunamigenic sources that surround these islands, instead of simply focusing on a single scenario as is common in previous studies (e.g., [16]). Second, we include estimates of population exposure and evacuation potential of non-residential groups, such as employees in businesses in low-lying coastal areas and tourists on cruise ships, whereas previous studies have focused only on residents (e.g., [12,17,18]) or a mix of residents and tourists but no explicit recognition of employees (e.g., [19,20]). We run multiple evacuation-modeling scenarios to assess the influence of departure delays and travel speeds on evacuation potential. Finally, we discuss the implications of our analysis for outreach and mitigation to increase community resilience to tsunamis in the U.S. Virgin Islands. This information may aid tsunami-planning efforts in the U.S. Virgin Islands, as well as insights on the vulnerability of other island communities with similar physical and population characteristics throughout the world.

2. Methods

2.1. Tsunami hazard zones for the U.S. Virgin Islands

The U.S. Virgin Islands are located in a complex seismic region and are surrounded by several tsunamigenic sources [4,21–24]. For this analysis, we use tsunami-modeling results summarized in Moore and Arcas [4] that represent 13 credible tsunamigenic sources for USVI coastal communities (Table 1; Fig. 1). These scenarios were selected for population-exposure and evacuation analysis based on discussions on relevant tsunamigenic sources and credible magnitudes with USVI and Puerto Rico representatives of the U.S. National Tsunami Hazard Mitigation Program [25] and guidance provided by the Intergovernmental Coordination Group of the Early Warning System for Tsunamis and Other Coastal Threats in the Caribbean Sea and Adjacent Regions (ICG/CARIBE-EWS) Hazard Assessment Working Group (WG2)[26]. Source parameters for each source are listed in Table 1 and discussed in more detail elsewhere [9,27–30, 4].

Tsunami generation, propagation, and inundation summarized in Moore and Arcas [4] were modeled using the high-performance Tsunami Hyperbolic Systems and Efficient Algorithms (Tsunami-HySEA) software [31,32] that has been validated with laboratory and field benchmarks for modeling of coastal currents and inundation [33–36]. Tsunami generation in the Tsunami-HySEA finite-volume numerical model is determined using the fault deformation model summarized in Okada [37] and parameters listed in Table 1. Additional details on the numerical methods and assumptions for Tsunami-HySea are summarized elsewhere [31,32]. Digital elevation models (DEM) for the tsunami propagation and inundation modeling summarized in Moore and Arcas [4] include two 1/3 arc-second (∼10-m) DEMs (one covering St. Croix Island and the other covering St. Thomas and St. John Islands) and one 1 arc-second (∼30-m) DEM depicting the region around USVI [38]. Final outputs provided in Moore and Arcas [4] include the extent of overland inundation and wave-arrival time in minutes.

2.2. Population distribution in tsunami hazard zone

To discuss population exposure and evacuation potential to USVI tsunami scenarios, we focused on residents, employees, and cruise ship passengers as one example of temporary tourist. We provide estimates for the total number of a population type that may be in tsunami-hazard zones but do not further manipulate population data to describe certain scenarios. The high number of combinations of daytime vs. nighttime, weekday vs. weekend, and time of year scenarios precludes our ability to choose one scenario over other

Table 1
Source parameters for USVI tsunami scenarios modeled in Moore and Arcas [4] and used in this study for population exposure and evacuation potential.

Scenario	Seismic Source	Mw	Long (°W)	Lat (°N)	Depth (km)	Length (km)	Width (km)	Slip (m)	Dip (°)	Strike (°)	Rake (°)
1867	Anegada Passage	7.8	65.000	18.000	9	50	25.00	12.0	−45	255	90
AP8	Anegada Passage	7.6	−64.265	18.457	4	49	32.18	4.8	25	50	−160
AP14	Anegada Passage	7.7	−65.684	18.064	4	84	34.17	3.9	23	103	−174
AP15	Anegada Passage	7.6	−65.670	17.755	4	49	32.18	4.8	65	67	−20
AP17	Anegada Passage	7.4	−64.813	18.022	4	64	28.56	2.0	45	260	95
AP20	Anegada Passage	7.4	−64.335	18.359	4	64	28.56	2.0	45	287	85
AP21	Anegada Passage	7.6	−65.110	18.036	4	48	32.80	4.8	70	290	153
AP25	Anegada Passage	7.6	−64.711	18.279	4	48	32.80	4.8	47	295	12
FSCDB	Full South Caribbean Deformed Belt	8.9	−69.6913	13.135	20	585	90.00	8.0	20	97	90
LA	Lesser Antilles Trench	8.5	−60.685	16.958	39	220	65.00	10.0	45	325	90
LA2	Lesser Antilles Trench	8.5	−62.990	19.000	39	220	65.00	10.0	45	300	90
PRTG	Puerto Rico Trench	9.1	−66.000	19.500	25	600	150.00	11.9	15	92	50
PRT2	Puerto Rico Trench	8.7	−66.505	19.254	20	500	110.00	8.0	20	86	45

possibilities.

The number and distribution of residents in USVI hazard zones were estimated based on the integration of polygonal data of 2020 Census Bureau block counts [39] and geospatial points related to residential structures in the National Structure Inventory (NSI)[40]. The number of residents at each residential-related structure varies; therefore, we created code weights based on NSI code descriptions to use in distributing populations (Table 2). All NSI codes noting single family residences and manufactured homes were given a weight of 1. For multi-family housing, we assigned code weights based on the lower end of the range. For example, code "RES3D" describes multi-family housing with 10–19 units and was assigned a code weight of 10. Some hotels were inadvertently categorized in the residential classes as "RES4" but were excluded in our analysis because it would be inappropriate to assign residential populations to hotels. Code weights for institutional dormitories and nursing homes were assigned differently than single- and multi-family housing. In both cases, we divided the 2020 national population for each category [39] by the number of NSI points with that specific code to estimate an average population at each location. These numbers were then divided by the 2023 average persons per household [41], resulting in code weights of 14 for institutional dormitories and 6 for nursing homes. These weights are not absolute counts but instead relative weights, i.e., we assume there are 6 times the number of people in a nursing home than there are in a single-family residence in the same census block. To calculate final residential population counts for each NSI point, we first divided the total population count for a given Census block that overlapped with a tsunami-hazard zone by the sum of code weights in that block and then multiplied that value by the code weight at an individual NSI point. NSI points located in hazard zones for a specific tsunami scenario were then tagged, and point-level population estimates were summed by island of the USVI.

Employee locations and counts were taken directly from the 2022 NSI database [40], where the employee-number field is considered a private attribute accessible only to federal users. USVI employee counts in the 2022 NSI database are not actual employee counts for individual businesses and instead are calculated based on average square footage per employee for a given occupancy type and square footage of each structure. Therefore, hazard-exposure results are intended to provide insight on the general magnitude of employees in hazard zones and not definitive assessments.

To provide insight on cruise ship passengers, we compiled cruise ship schedules for fiscal year 2025 (October 1, 2024 to September 30, 2025) for the three primary USVI ports, including maritime facilities in Crown Bay, St. Thomas Island; Havensight, St. Thomas Island; and Frederiksted, St. Croix Island, as defined by the Virgin Islands Port Authority (2024)(Fig. 1). Cruise ships cannot dock directly on St. John Island; instead, ships anchor offshore and ferry passengers often to a National Park Service (NPS) dock in Cruz Bay Harbor [42,43]. Passenger counts for each vessel type was estimated based on websites for cruise ship companies or third-party providers [44].

2.3. Pedestrian evacuation potential

Manual interpretation of tsunami hazard zones summarized in Moore and Arcas [4] and NSI points suggests that estimating pedestrian evacuation potential does not require computer-based evacuation modeling for every scenario and island of the USVI. In several tsunami scenarios for certain islands, events do not produce substantial overland inundation, distances to exit hazard zones are less than 50 m, and wave-arrival times are estimated to be 20 min or greater. In these situations, we assigned evacuation travel times with no departure delay to be 1 min. Pedestrian-evacuation modeling was reserved for scenarios that had shorter wave-arrival estimates and greater distances to safety, including the 1867 (St. Thomas and St. John Islands only), AP15 (St. Croix Island only), AP17, AP20 (St. Croix Island only), AP21 (St. Croix Island only), and AP25 (St. Croix and St. Thomas Islands) scenarios (Table 1). The focus on specific islands for further evacuation modeling was based on the presence or non-presence of residents in areas with short wave-arrival times. Also, as noted in the Results section, pedestrian-evacuation modeling was also done for the PRTG scenario given the high number of residents in USVI hazard zones.

Table 2
National Structure Inventory [40] codes and code descriptions, as well as code weights derived for this study.

NSI code	Code description	Code weight
RES1-1SNB	Single Family Residential, 1 story, no basement	1
RES1-1SWB	Single Family Residential, 1 story, with basement	1
RES1-2SNB	Single Family Residential, 2 story, no basement	1
RES1-2SWB	Single Family Residential, 2 story, with basement	1
RES1-3SNB	Single Family Residential, 3 story, no basement	1
RES1-3SWB	Single Family Residential, 3 story, with basement	1
RES1-SLNB	Single Family Residential, split-level, no basement	1
RES1-SLWB	Single Family Residential, split-level, with basement	1
RES2	Manufactured Home	1
RES3A	Multi-Family housing 2 units	2
RES3B	Multi-Family housing 3–4 units	3
RES3C	Multi-Family housing 5–10 units	5
RES3D	Multi-Family housing 10–19 units	10
RES3E	Multi-Family housing 20–50 units	20
RES3F	Multi-Family housing 50 plus units	50
RES4	Average Hotel	Excluded
RES5	Institutional Dormitory	14
RES6	Nursing Home	6

For tsunami scenarios that warranted pedestrian-evacuation modeling, we applied a least-cost-distance (LCD) approach (e.g., [45]), which uses geographic information system (GIS) tools to calculate the shortest path to safety from every location in a hazard zone, with the difficulty of traveling through each location represented as a cost surface based on static landscape conditions related to land cover and slope. Agent-based models reflecting individuals and their behavior while evacuating have also been applied to tsunami studies (see [46] for a review) but we applied an LCD-based approach to allow us to map evacuation travel times across large areas that were not anchored to specific population scenarios and temporal or behavioral assumptions.

Pedestrian travel times to safety are based on an LCD model implemented in Esri ArcPro 10.3.3 GIS software (Redlands, California) that considers the slope and land cover of an area to calculate the most efficient paths on foot to safety from every location in a hazard zone [45,47,48]. Pedestrian travel times out of tsunami-hazard zones were estimated using an anisotropic, path distance model where the difficulty of traveling through each location is represented as a cost in terms of increased travel time. Anisotropy incorporates direction of travel, and the path-distance algorithm calculates distances and slopes between cells of varying elevations. To model pedestrian evacuations, land cover and elevation derived slope data are transformed into raster grids of speed conservation values (SCVs), which represent the proportion of maximum travel speeds that are expected at a location based on local conditions. SCVs can range from 0 (indicating that no travel is permitted through a grid cell) to 1 (indicating that maximum travel speeds are maintained). The modeling then estimates travel directions based on optimal routes of least costs (lowest amount of time in our case), which can be used to estimate overall travel times along an evacuation path for any maximum speed under ideal conditions (i.e., slightly downhill with paved streets). Slope SCVs are based on Tobler's [49] hiking function and slopes were derived from 2020, 1-m resolution, LiDAR-derived elevation data [50]. For landcover SCVs, we constrained pedestrian travel to road networks by assigning a SCV value of 1 for road segments derived from the National Transportation Dataset [51] and then buffered by 5 m. Path-distance grids based on road travel and slope values are then transformed to travel time maps based on multiple maximum travel speed assumptions. To test the influence of travel speeds on evacuation potential, we created travel time maps for select islands and scenarios assuming a slow-walking speed (1.2 m/s) and a fast-walking speed (1.52 m/s)[16,52].

We also test the influence of departure delays on evacuation potential because departure delays have been documented in past tsunami disasters [53–58]. Research summarized in Makinoshima and Imamura [58] on evacuation behavior during the 2011 Tohoku tsunami disaster suggests that most people did not immediately evacuate and instead required at least 4 min after the earthquake to initiate an evacuation, either due to strong ground motions or the time required to prepare. In our study, we test the influence of departure delays on evacuation potential by estimating the number of people that may have insufficient time to evacuate assuming no departure delay, a 5-min delay, and a 10-min delay.

The amount of time available to evacuate for a specific NSI point in a tsunami-hazard zone is determined by assigning the travel-time value for the closest road segment. If no road segments were within 50 m of a point, we assigned a travel-time value of 1 min. This occurred if a house was in a hazard zone but a driveway and the road used to leave the house were out of the hazard zone. In this situation, a person would effectively need to get to their driveway to evade tsunami waves.

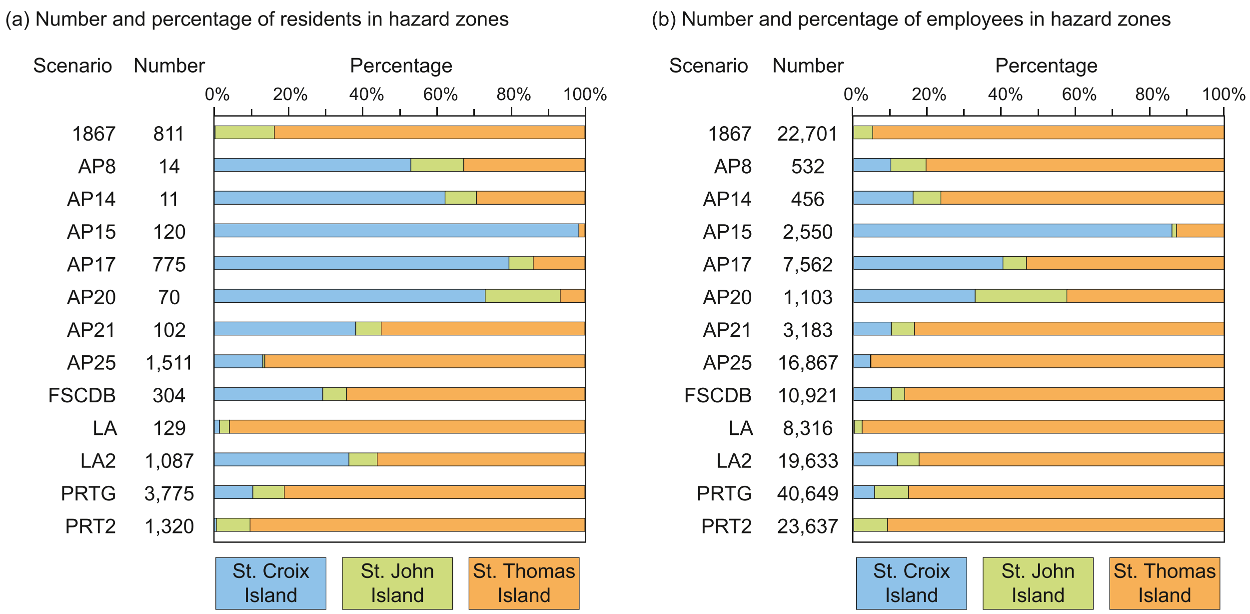

Fig. 2. Number and percentage by island of (a) residents and (b) employees in USVI tsunami-hazard zones. Scenario acronyms are provided in Table 1.

3. Results

3.1. Resident exposure and evacuation potential to tsunami scenarios

Based on 2020 population counts, we estimate that the number of residents in USVI tsunami-hazard zones ranges from 11 residents for the AP14 scenario to 3775 residents for the PRTG scenario (Fig. 2a). This is an approximation that may be too high because all individuals accounted for in census data may not be at their primary residence during a future event or may be too low because of guests at homes or other people in the tsunami-hazard zone. Results indicate that certain tsunami scenarios may impact certain islands more than others. For example, the residential exposure to tsunami scenarios associated with the Puerto Rico Trench (PRTG, PRT2) is primarily on St. Thomas Island, whereas several of the tsunami scenarios associated with Anegada Passage (AP14, AP15, and AP17) have higher residential exposures on St. Croix Island.

The distribution of residents as a function of wave-arrival estimates varies among the 13 scenarios (Fig. 3a). Estimated wave arrival is on the order of tens of minutes or less for several of the scenarios associated with an earthquake generated in the Anegada Passage (e.g., AP15, AP17, AP20, AP21, and AP25) (Fig. 1). A second set of scenarios have wave-arrival times more on the order of 30–45 min, such as a repeat of the 1867 event, the two scenarios associated with the Puerto Rico Trench (PRT2 and PRTG), and one of the Lesser Antilles scenarios (LA2). Wave-arrival times for resident populations for the third set of scenarios (FSCDB and LA) are on the order of an hour or more.

Results also indicate variability in residential exposure in terms of wave-arrival times for the different islands (Fig. 4). There are only a few scenarios (e.g., AP8, LA, PRTG, and PRT2) in which the distribution of residents is similar. For the remaining scenarios, residents of one island are estimated to have less time to evacuate than other islands. For example, residents in St. Thomas Island who are in tsunami-hazard zones for the LA2, AP17, and AP21 scenario may have twice the amount of time available for evacuations than residents in St. Croix Island. For the AP17 scenario, St. Croix Island residents may have approximately 5–10 min before wave arrival, which is within the time frame that people may delay their departures (i.e., the 5- and 10-min departure delays assumed in the evacuation-modeling results).

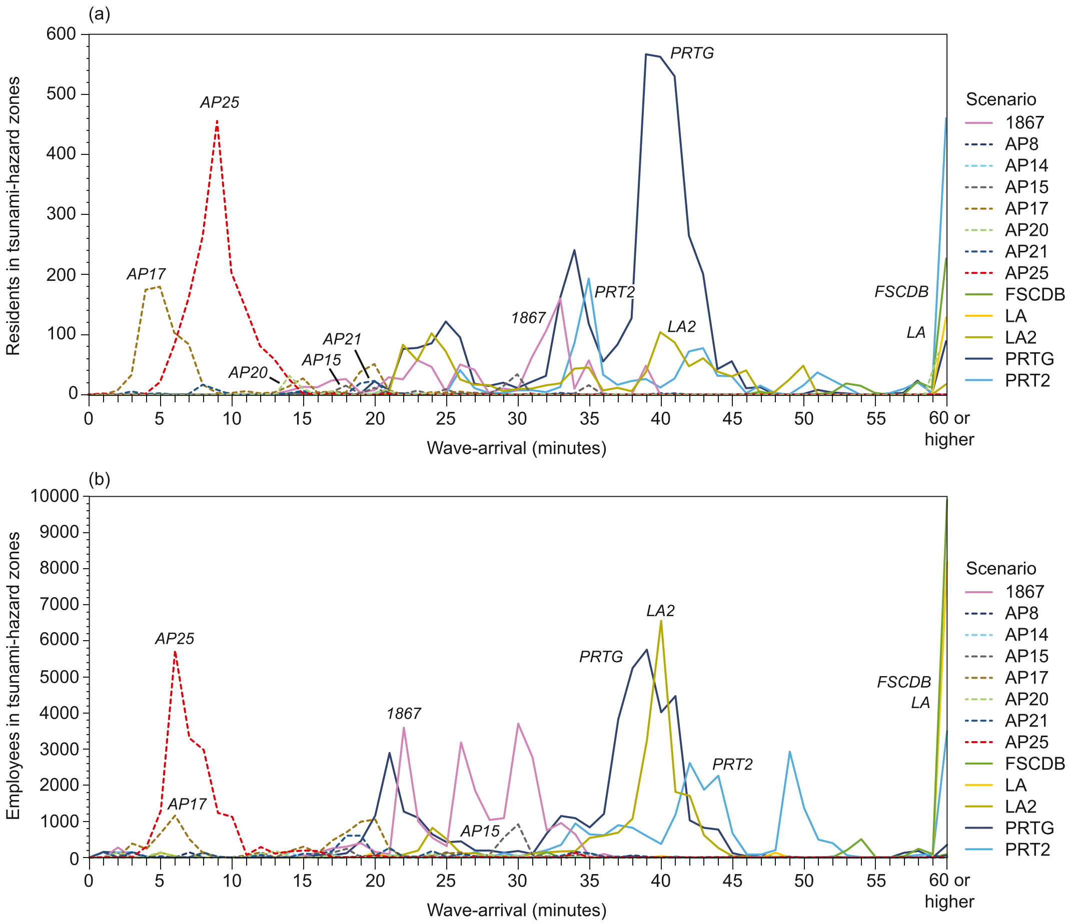

Fig. 3. Distribution of (a) residents and (b) employees for each tsunami scenario in this study, organized by estimated wave-arrival time. Scenario acronyms are explained in Table 1.

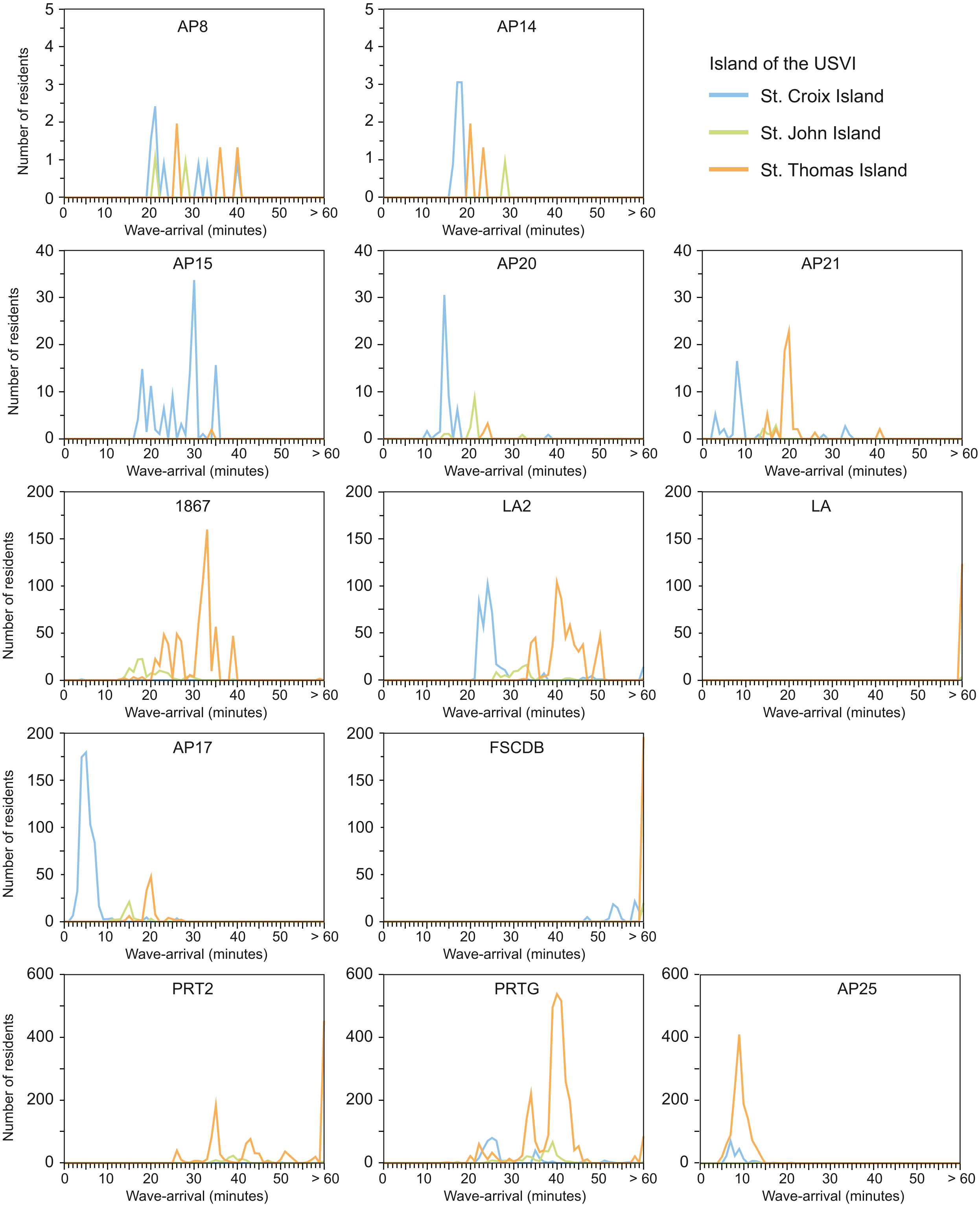

Fig. 4. Distribution of residents for each tsunami scenario in this study (Table 1), organized by estimated wave-arrival time and island of the USVI. Scenarios are grouped here by the range of resident values on the y-axis to highlight these ranges. Scenario acronyms are explained in Table 1.

Based on the limited extent of overland inundation and wave-arrival times on the order of 20 min or more for most scenarios (Figs. 3a and 4), we assume travel time out of hazard zones for these scenarios is 1 min. However, given the shorter wave-arrival estimates, pedestrian-evacuation modeling as described in the Methods section was conducted to estimate travel times out of hazard zones for the 1867, AP15 (St. Croix Island only), AP17, AP20 (St. Croix Island only), AP21 (St. Croix Island only), and AP25 (St. Croix and St. Thomas Islands) scenarios. The focus on specific islands for further evacuation modeling was based on the presence or non-presence of residents in areas with short wave-arrival times (Fig. 4). We also modeled evacuation travel times for the PRTG scenario given the high population exposure to tsunami hazards.

Only one scenario (AP17) has residents with insufficient time to evacuate before wave arrival assuming no departure delay (Table 3). There are 25 residents in tsunami-hazard zones associated with the AP17 scenario with modeled travel times to safety (assuming no delay) that are greater than wave-arrival times, which are on the order of minutes after generation (Fig. 3). If one assumes a 5-min departure delay, then four scenarios have residents with insufficient time, namely the 1867 (1 person), AP21 (8 people), AP25 (411 people), and AP17 (447 people). The same four scenarios have larger numbers of residents if one assumes a 10-min departure delay and the AP20 scenario is added with 2 people with insufficient time to evacuate.

The influence of faster travel speeds on reducing the number of residents with insufficient time to evacuate before wave arrival was examined for these five scenarios (Table 4). Estimates in Table 4 are based on a fast-walking speed (1.52 m/s), as opposed to a slow-walking speed (1.2 m/s)[16,52]. Results demonstrate that increasing travel speeds reduces the number of residents with insufficient time to evacuate, ranging from 5 fewer people in the AP17 hazard zone (assuming no departure delay) to 119 fewer people in the AP25 hazard zone (assuming a 10-min departure delay). While there are reductions related to increasing travel speeds, far more people can reach safety by reducing departure delays.

3.2. Employee exposure and evacuation potential to tsunami scenarios

We estimate that the number of employees in USVI tsunami-hazard zones ranges from 456 employees for the AP14 scenario to 40,649 employees for the PRTG scenario (Fig. 2b). This is an approximation that may be too high because all employees of a business may not be working at the same time or may be too low because NSI employee data was based on business type and square footage of structures and not confirmed employee counts from each business. However, with these caveats in mind, estimates still demonstrate that the number of employees in USVI tsunami-hazard zones is substantially larger than the number of residents in these same zones. Similar but to a lesser degree to residential exposure, certain tsunami scenarios have higher percentages of employee exposure on certain islands. For example, employee exposure is relatively higher on St. Croix Island for the AP15 scenario (Fig. 2b). However, for the remaining tsunami scenarios, the highest percentage of employee exposure is on St. Thomas Island.

The distribution of employees as a function of estimated wave-arrival times for each USVI tsunami scenario is largely similar to the distribution of residents (Fig. 3b) but with some noticeable differences. The general wave-arrival time for the bulk of employees is faster than for residential locations for several scenarios, such as AP25 (10 min reduced to 5 min) and 1867 (~32 min reduced to 20 min) scenarios. These differences demonstrate how waterfront areas closest to the shore are primarily populated by employees. In general, the three general sets of scenarios remain, such as scenarios with employee distribution in areas where estimated wave arrival is on the order of tens of minutes or less (e.g., AP17, AP20, AP21, and AP25), scenarios with wave-arrival times more on the order of 20–45 min (e.g., 1867, PRT2, PRTG, and LA2), and scenarios with wave-arrival times of an hour or greater (FSCDB and LA).

With regard to evacuation potential, nine of the 13 scenarios have no employees in areas where wave-arrival times are larger than pedestrian travel times, assuming no departure delays. The remaining four scenarios that do have employees in areas with travel times

Table 3

Number of residents in USVI tsunami-hazard zones and those that may have insufficient time to evacuate hazard zones before wave arrival, organized by scenario. Travel times out of hazard zones are based on evacuation modeling assuming a slow-walking speed (1.2 m/s) for certain scenarios or assumed to be 1 min for other scenarios, which is described in the Methods section. Estimates include the total number of residents in tsunami-hazard zones and the number of residents with travel times that are larger than modeled wave-arrival times, assuming no departure delay, a 5-min departure delay, and a 10-min departure delay. Scenario acronyms are provided in Table 1.

Tsunami Scenario	In Hazard Zone	Number of residents with insufficient time to evacuate hazard zones before wave arrival, given various departure-delay assumptions		
		No Delay	5 min	10 min
1867	811	0	1	1
AP8	14	0	0	0
AP14	11	0	0	0
AP15	120	0	0	0
AP17	775	25	447	604
AP20	70	0	0	2
AP21	102	0	8	34
AP25	1511	0	411	1396
FSCDB	304	0	0	0
LA	129	0	0	0
LA2	1087	0	0	0
PRTG	3775	0	0	0
PRT2	1320	0	0	0

Table 4
Number of residents in USVI tsunami-hazard zones and those that may have insufficient time to evacuate hazard zones before wave arrival, organized by scenario. Travel times out of hazard zones are based on evacuation modeling assuming a fast-walking speed (1.52 m/s) [16]. Estimates include the total number of residents in tsunami-hazard zones and the number of residents with travel times that are larger than modeled wave-arrival times, assuming no departure delay, a 5-min departure delay, and a 10-min departure delay.

Tsunami Scenario	In Hazard Zone	Number of residents with insufficient time to evacuate hazard zones before wave arrival, given various departure-delay assumptions		
		No Delay	5 min	10 min
1867	811	0	1	1
AP17	775	20	374	517
AP20	70	0	0	2
AP21	102	0	4	25
AP25	1511	0	68	1277

Table 5
Number of employees in the tsunami-hazard zone and those that may have insufficient time to evacuate hazard zones before wave arrival, organized by scenario. Travel times out of hazard zones are based on evacuation modeling assuming a slow-walking speed (1.2 m/s)[16,52] for certain scenarios or assumed to be 1 min for other scenarios, which is described in the Methods section. Estimates include the total number of employees in tsunami-hazard zones and the number of employees with travel times that are greater than modeled wave-arrival times, assuming no departure delay, a 5-min departure delay, and a 10-min departure delay.

Tsunami Scenario	In Hazard Zone	Number of employees with insufficient time to evacuate hazard zones before wave arrival, given various departure-delay assumptions		
		No Delay	5 min	10 min
1867	22,701	131	282	282
AP8	532	0	164	304
AP14	456	0	0	28
AP15	2550	0	0	13
AP17	7562	93	1743	3049
AP20	1103	0	297	304
AP21	3183	0	328	474
AP25	16,867	564	6661	15,685
FSCDB	10,921	0	0	0
LA	8316	0	0	0
LA2	19,633	0	131	299
PRTG	40,649	136	282	570
PRT2	23,637	0	282	282

to safety that are higher than wave-arrival times (assuming no departure delays) include AP17 (93 employees), 1867 (131 employees), PRTG (136 employees), and AP25 (564 employees) (Table 5). Assuming a 5-min departure delay, there are 9 scenarios with employees with insufficient time to evacuate, ranging from 131 employees (LA2) to 6661 employees (AP25). Assuming a 10-min departure delay, eleven of the thirteen scenarios have employees with insufficient time to evacuate and the highest number of employees with insufficient time rises to 15,685 (Table 5).

Several of the scenarios noted as having employees with insufficient time to evacuate reflect employees located on docks where estimated wave-arrival times are on the order of 2–6 min depending on the scenario, even though overland inundation may not occur until 30 min or more later. These wave-arrival estimates may be representing the time at which changes in water level occur under the dock and not actual inundation of the dock or the business on the dock. Further studies may be necessary to support any claim that employees in these locations are threatened by tsunami hazards for certain scenarios. This situation may be applicable to hazard-

Table 6
Number of employees in the tsunami-hazard zone and those that may have insufficient time to evacuate hazard zones before wave arrival, organized by scenario. Travel times out of hazard zones are based on evacuation modeling assuming a fast-walking speed (1.52 m/s)[16]. Estimates include the total number of employees in tsunami-hazard zones and the number of employees with travel times that are greater than modeled wave-arrival times, assuming no departure delay, a 5-min departure delay, and a 10-min departure delay.

Tsunami Scenario	In Hazard Zone	Number of residents with insufficient time to evacuate hazard zones before wave arrival given various departure-delay assumptions		
		No Delay	5 min	10 min
PTRG	40649	131	282	289
AP15	2550	0	0	13
AP17	7562	10	1718	3044
AP21	3183	0	328	474
AP25	16867	479	6287	15,680

exposure estimates of employee for the PRT2, LA2, 1867, AP8, AP14, and AP20 scenarios based on a manual interpretation of imagery, employee locations, and wave-arrival estimates.

With this in mind, we focused on a subset of tsunami scenarios on the remaining scenarios (PRTG, AP15, AP17, AP21, and AP25) to test the influence of faster travel speeds on reducing the number of employees in areas with insufficient time to evacuate before wave arrival (Table 6). Estimates in Table 6 are based on a fast-walking speed (1.52 m/s), as opposed to a slow walk (1.2 m/s). Results demonstrate that increasing travel speeds reduces the number of employees with insufficient time to evacuate, ranging from 5 fewer people in the PTRG hazard zone (assuming no departure delay) to 374 fewer people in the AP25 hazard zone (assuming a 5-min departure delay). However, although there are reductions related to increasing travel speeds, far more employees can reach safety by reducing departure delays.

3.3. Tourist exposure and evacuation potential to USVI tsunami scenarios

Our analysis of cruise ship schedules indicates 73 different vessel types are berthed at USVI ports over the course of a year. We do not assume every passenger on a cruise ship disembarks at every port for the full duration of a visit; however, analyzing the number of passengers and duration of cruise ship visits does provide some insight into the magnitude of tourists that may enter USVI tsunami-hazard zones. We do not provide estimates of the number of crew members per cruise ship because it is unlikely that many of them would go ashore when a ship is docked. However, some crew members may disembark during a USVI stop, thereby adding to the number of people in tsunami-hazard zones. The maximum daily value of passengers on these cruise ships varies (Table 7), ranging from 1964 passengers ferried to Cruz Bay Harbor, St. John Island, to 17,894 passengers in Havensight, St. Thomas Island. Cruise ships vary in passenger counts from several hundred to several thousand; therefore, the high maximum daily number of passengers at a USVI pier summarized in Table 7 reflects multiple ships that are docked at the same time.

Compiling duration data and passenger data for the various cruise ships that temporarily berth at USVI maritime facilities indicates that tourists are a common presence along certain areas of the USVI waterfront. For example, cruise ships of various sizes and for various durations are docked in St. Thomas Island cumulatively for 180 days over a year (49 %) at the Havensight pier and 140 days (38 %) in Crown Bay (Fig. 5). These two locations have many days over the course of a year (77 in Crown Bay and 18 in Havensight) where the number of passengers on cruise ships docked with overlapping time periods can total over 10,000 people.

The potential for and extent of inundation from the 13 tsunami scenarios varies among the four maritime sites (Fig. 6) based on a manual interpretation of tsunami-inundation models summarized in Moore and Arcas [4] and 0.6-m resolution satellite imagery [59]. All tsunami scenarios inundate piers in Frederiksted (St. Croix Island) and Havensight (St. Thomas Island) but to varying degrees. Several of the scenarios (1867, AP17, AP25, PRT2, PRTG) only inundate the tip of the Havensight pier and not the primary area with buildings. Most scenarios only inundate small portions of the Frederiksted pier, whereas the modeled inundation from the AP25 scenario covers most of the pier. Inundation modeling at the NPS service dock in St. John Island suggests complete inundation from most of the scenarios, except for partial inundation from the AP8 and AP14 scenarios and no observed inundation for the AP15 and AP25 scenarios. Inundation modeling at the Crown Bay (St. Thomas Island) maritime facility suggests complete inundation from several scenarios (1867, AP25, LA2, PRTG and PRT2), partial inundation from the FSCDB and AP17 scenarios, and no observed inundation from the remaining scenarios. No analysis was done to evaluate if and how cruise ships may be impacted by tsunami waves or any potential life-safety issues for crew or passengers on these ships if a tsunami were to occur.

4. Discussion

Results presented here demonstrate that discussing population vulnerability to tsunamis in island communities may be more complicated than single scenarios or simple distinctions of local or distant sources. Our study examines the nuances of population vulnerability to tsunami hazards on islands in complex seismic regions using a case study of the U.S. Virgin Islands. In this section, we discuss the implications of our results on tsunami evacuation planning, not only in USVI, but also in coastal communities elsewhere throughout the world with similar tsunami potential.

Table 7
Maximum daily number of passengers on cruise ships between October 1, 2024 to September 30, 2025 that dock at USVI ports in Crown Bay, St. Thomas Island; Havensight, St. Thomas Island; and Frederiksted, St. Croix Island, as defined by Virgin Islands Port Authority (2024). Noted with an asterisk, cruise ships cannot dock directly on St. John Island; instead, ships anchor offshore and ferry passengers often to a National Park Service (NPS) dock in Cruz Bay Harbor [42,43].

Pier Location	Maximum Daily Number of Passengers
Crown Bay, St. Thomas Island	17,894
Havensight, St. Thomas Island	12,968
Frederiksted, St. Croix Island	6140
Cruz Bay Harbor*, St. John Island	1964

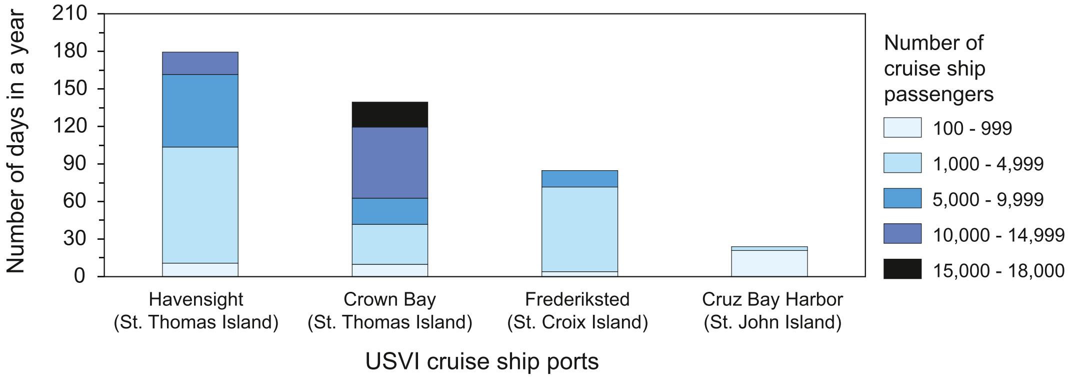

Fig. 5. Number of days in a year based on the number of passengers on cruise ships scheduled between October 1, 2024 to September 30, 2025 to be docked at USVI ports in Havensight, St. Thomas Island; Crown Bay, St. Thomas Island; and Frederiksted, St. Croix Island, as defined by Virgin Islands Port Authority (2024). Cruise ships cannot dock directly on St. John Island; instead, ships anchor offshore and ferry passengers often to a National Park Service (NPS) dock in Cruz Bay Harbor [42,43].

Fig. 6. Tsunami inundation potential for USVI maritime facilities in Crown Bay (St. Thomas Island), Frederiksted (St. Croix Island), Havensight (St. Thomas Island) and Cruz Bay Harbor (St. John Island), as defined by Virgin Islands Port Authority (2024), based on a manual interpretation of tsunami-inundation models summarized in Moore and Arcas [4] and satellite imagery. Cruise ships cannot dock directly on St. John Island; instead, ships anchor offshore and ferry passengers often to a National Park Service (NPS) dock in Cruz Bay Harbor [42,43]. Blue circles note that modeling indicates that a maritime facility is inundated, either partially or completely, by a specific tsunami scenario. An open circle notes that modeling suggests no inundation at a maritime facility.

4.1. Variations in population vulnerability

Tsunamis threaten USVI coastal communities, but results demonstrate that population vulnerability is not the same for all population groups across all islands for all tsunami scenarios. First, there is a wide range of residential and employee exposure to the 13 scenarios in this study, ranging from 11 to 3775 residents and 456 to 40,649 employees (Fig. 2) and the evacuation potential for these scenarios also vary (Tables 3 and 5). Certain tsunami scenarios are more threatening to residents in St. Thomas Island (AP21, AP25, LA, LA2, PRTG, PRT2, and 1867), others are more threatening to residents in St. Croix Island (AP15, AP17, and AP20), and all scenarios generally have far lower population exposure in St. John Island than in the other islands (Figs. 2 and 4).

The range in potential impacts from various sources may create challenges for tsunami outreach and preparedness efforts because at-risk individuals may not be able to differentiate tsunamigenic sources and related distances to safety for their island location in the minutes to tens of minutes before wave arrival. As such, pre-event outreach and preparedness efforts may instead emphasize maximum tsunami-evacuation zones based on a composite of the 13 tsunami-hazard scenarios addressed in this study. Current tsunami-evacuation maps in USVI are based on the 25 m (82 feet) topographical contour to recognize the various tsunami sources [60,61]. Although evacuation maps based on composite zones or elevation contours support the lowest risk tolerance to minimize loss of life, this approach may also create unintended evacuation challenges. First, populations outside of hazardous areas for an imminent tsunami but inside a larger composite evacuation zone may evacuate, creating what are referred to as shadow evacuations [62] and possibly adding to congestion of evacuation corridors. Second, these same individuals in a shadow evacuation may later believe that they did not need to evacuate and that pre-event, tsunami-outreach efforts exaggerated the tsunami threat to a community, possibly reducing trust in future warnings. One strategy to manage these evacuation and outreach challenges has been the use of multiple evacuation zones that reflect specific tsunamigenic sources or regions. For example, tsunami-evacuation "playbooks'' have been implemented jointly by the California Geological Survey and the California Office of Emergency Services to provide evacuation guidance for tsunamis based on estimated wave-arrival times of less than or more than 4 h [63–65]. This approach differentiates local threats where self-evacuations may be necessary and distant sources that will be facilitated by public officials over several hours [63]. In our USVI case study, the concept of multiple evacuation zones may be possible for certain USVI tsunami scenarios, such as the LA, LA2, or FSCDB, due to wave-arrival times on the order of 60 min and higher (Figs. 3 and 4) but may warrant substantial discussions given potential technical and communication challenges.

Results also indicate that employee exposure is consistently an order of magnitude higher than residential exposure for all scenarios and that most employe exposure is in St. Thomas Island. Shorter wave-arrival times for employees for certain scenarios (e.g., AP25, 1867, and PRTG) suggests that areas closest to the shore in USVI are more likely occupied by businesses with employees, and possible customers, than residents. There is limited literature on employee vulnerability to tsunamis (e.g., [16,65]). Some studies recognize residents and tourists (e.g., [66,67]) with the possible assumption that employees and residents in hazard zones may be the same people. In our case study, there is an order of magnitude difference in the tsunami-hazard exposure of residents and employees (Fig. 2). For example, we estimate that there are 3775 residents and 40,649 employees in the modeled tsunami-inundation zone for the PRTG scenario (Fig. 2). If tsunami-outreach efforts only target residents in hazard zones, then those efforts may be missing a substantial number of people threatened by tsunamis.

The high number (Table 7) and persistent presence (Fig. 4) of cruise-ship passengers along USVI shorelines also indicate the importance of recognizing tourist populations when discussing population vulnerability to tsunami threats. Fathianpour et al. [13] also discuss the importance of including tourist-related challenges in developing effective and realistic tsunami-evacuation plans. In our case study, the maximum daily number of passengers of cruise ships in four locations (Table 7) far exceeds the number of residents in the various tsunami scenarios across the entire USVI (Table 3). To date, there has limited attention in the literature related to the tsunami vulnerability of cruise ships, aside from determining evacuation areas outside of ports and developing action plans if there is sufficient time to move a vessel before tsunami wave arrival (e.g., [68–70]). Moving cruise ships may be unlikely for USVI ports given wave-arrival times on the order of minutes to tens of minutes for most scenarios discussed here (Figs. 3 and 4). The focus of these studies has also been on the resilience of the ships and not on the approximately 2000 to 20,000 tourists (and possibly cruise ship crew members) that may be on waterfront areas (Table 7) if a tsunami were to occur. The persistence of cruise ships over a year at USVI maritime facilities (Fig. 5) also demonstrates the importance of recognizing cruise-ship passengers in tsunami-related risk assessments (e.g., [12]).

4.2. Reducing departure delays to increase evacuation potential

The amount of available time to evacuate before wave arrival for the 13 tsunami scenarios varies by scenario and by island (Figs. 3 and 4), ranging from 5 to 15 min for several scenarios associated with earthquakes generated in the Anegada Passage (e.g., AP17) to over an hour for the FSCB and LA scenarios. Results suggest that most residents and employees in our study area may have sufficient time to evacuate from all tsunami scenarios assuming no departure delay. Exceptions to this are 25 residents from the AP17 scenario (Table 3) and between 93 and 564 employees for four scenarios (AP17, AP25, PRTG, and 1867) (Table 5). Immediate evacuations may not be realistic, as departure delays have been documented in past tsunami disasters [54,57,58] and expected by emergency managers in future events [13]. If one assumes 5- or 10-min departure delays, the number of residents and employees who may have insufficient time to evacuate before wave arrival increases substantially, not only for these tsunami scenarios but for many others. Results also demonstrate that reducing departure delays had a far larger impact than increasing travel speeds on reducing the number of people with insufficient time to evacuate (Tables 4 and 6). This is primarily due to the short wave-arrival times for certain scenarios, such as AP17 and AP25 (Figs. 3 and 4), where there may be an insufficient amount of time before wave arrival to see substantial savings from increased travel speeds.

Regardless of reducing departure delays or increasing travel speeds, studies have shown pre-disaster education to be a critical factor in enabling successful evacuations from local tsunamis [71,72]. Results here can support pre-disaster education in two ways. First, educating at-risk individuals that successful evacuations are plausible for most scenarios with appropriate evacuation behavior can increase positive outcome expectancy, which is the anticipation of positive consequences due to certain actions and has been shown to influence intentions to prepare for future tsunamis [73]. Second, for scenarios or locations where risk-reduction strategies can demonstrate a reduction in loss of life (Tables 4 and 6), results can be used to support cost-benefit analyses where every potential life saved can be framed as saving $12.5 million (USD), which is the Value of a Statistical Life (VSL) for the base year of 2022 [74]. For example, outreach efforts that can reduce departure delays from 10 min to 5 min if the AP25 scenario were to occur may save 985 residential lives (Table 3), which can be construed as saving $12.3 billion (USD).

4.3. Areas for future research

The approaches described in this article explore variations in population vulnerability to tsunamis in a complex seismic region. However, we did not address several areas where additional research may be beneficial. One area for further research may be the behavioral and sociological aspects of potential tsunami-evacuation behavior of tourists (e.g., [13]) and, in our case study, as it specifically relates to cruise-ship passengers, cruise-ship personnel, and employees of land-based businesses in tsunami-hazard zones. Individual cruise-ship passengers and other tourists may have limited time in tsunami-hazard zones but may also have limited knowledge of how and where to seek high ground if a tsunami where to occur. Cruise-ship personnel and land-based employees may spend more time in tsunami-hazard zones than a cruise-ship passenger over time; therefore, understanding their perceptions and awareness of tsunamis may be critical, as these individuals may unofficially act as leaders to motivate unknowing tourists to evacuate. In addition to gauging tsunami perceptions of these various populations, assessing the impact of education efforts on affecting future evacuation behavior may be a related area of research, as previous studies have documented no significant increase in tsunami preparedness from increased awareness of tsunamis [75].

A second area for potential research may be natural-science studies to determine if at-risk individuals in USVI communities would feel ground shaking associated with the tsunamigenic seismic sources that generate tsunamis (Table 1). Previous studies on environmental cues as they relate to evacuations have documented the importance of associated potential tsunami wave generation with feeling the strong ground shaking of the initial earthquake [56,58,76].

A third area for potential research may focus on improving understanding of potential inundation and impact forces on USVI maritime facilities. In our cursory visual interpretation of imagery and tsunami-inundation models summarized in Moore and Arcas [4], some tsunami scenarios may completely inundate maritime facilities, others appear to partially inundate them, and some do not appear to inundate the facilities at all (Fig. 6). Additional studies may be warranted given the persistence of cruise ships throughout the year (Fig. 5) and the magnitude of cruise-ship passengers (Table 7) that may disembark into tsunami-hazard zones. A related area of potential research is how well cruise ships may withstand estimated wave-impact forces from these tsunamis, from the perspectives of the structural integrity of a vessel and the extent to which on-ship passengers may be jolted. As noted earlier, cruise-ship passengers are often ferried to St. John Island [42], and it is unclear how these smaller boats may perform during a tsunami.

5. Conclusions

This case study of characterizing population exposure and evacuation potential from tsunamis that threaten the U.S. Virgin Islands focused on the use of multiple scenarios, the recognition of different population groups in hazard zones, and the influence of departure delays on evacuation potential. Based on our approach and analysis, we reach several conclusions that could be considered when developing future research and applications to support data-driven, evacuation planning in island communities.

- The threat to life safety posed by tsunamis is not equal and instead varies based on the amount of time before wave arrival for each scenario. This aspect of time distinguishes tsunami hazards from other hazards where such a window for human action does not exist or is substantially limited.
- The number of employees and tourists in tsunami-hazard zones is orders of magnitude higher than the number of residents, suggesting that risk assessments that only account for residents are under-estimating threats to life safety from tsunamis.
- Reducing departure delays had a greater impact than increasing pedestrian travel speeds on reducing the number of people who may have insufficient time to evacuate hazard zones before wave arrival.

Characterizing and communicating the threat that tsunamis pose to island communities entails an appreciation of multiple tsunamigenic sources and the different response contexts that they each represent due to differences in estimated wave-arrival times. There has been considerable attention in the tsunami-evacuation literature devoted to single-source scenarios and residential populations. Results of this case study may provide new insights for risk-reduction and risk-communication strategies that recognize multiple sources and additional threats to non-residential populations in island communities.

CRediT authorship contribution statement

Nathan Wood: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jeff Peters:** Formal analysis, Data curation, Writing – review & editing. **Christopher Moore:** Formal analysis, Data curation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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does not imply endorsement by the U.S. Government.

Data availability

Geospatial data and associated metadata summarizing tsunami-inundation modeling used in this article can be found at Moore and Arcas [4]. Geospatial and tabular datasets related to population-exposure estimates and pedestrian-evacuation-modeling outputs are provided in Wood and Peters [44].

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