Pedestrian evacuation time calculation against tsunami hazard for southern coasts of Bodrum peninsula

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Abstract

Historical records with recent events reveal that tsunamis are threatening the western coast of Turkey due to the intensely active seismicity of the Eastern Mediterranean Sea. The most recent tsunami events in the region (30 October 2020 Izmir-Samos and 20 July 2017 Bodrum-Kos) restated that the cities located near the Eastern Mediterranean and connected seas should also consider tsunami events in their disaster mitigation plans. Bodrum is one of the most critical coastal districts vulnerable to marine hazards, with popular hotels, numerous coastal facilities, long and famous beaches, cultural, historical and touristic places. Tsunami evacuation planning is required for Bodrum district to mitigate the damage caused by destructive tsunami waves inundating on land. This study calculates the geospatial distribution of pedestrian evacuation time, based on selected credible worst-case scenarios. A widely used anisotropic least-cost distance model is applied via the Pedestrian Evacuation Analyst Tool to calculate the required time for a pedestrian to evacuate the region under tsunami threat based on the selected scenarios. The model includes landscape properties that affect the walking pace of pedestrians during an evacuation, such as elevation, slope, land cover, and land use types (beach, road, bushes, water bodies, and barriers). The resultant pedestrian evacuation time maps show that the maximum time needed for a pedestrian is 8, 6, 5, 4, and 3 min for highly populated coastal settlements of Bodrum, which are Central Bodrum, Yahsi, Akyarlar-Karaincir-Aspat Bays, Bitez, and Gumbet Bays, respectively.

Keywords Tsunami evacuation · Least-cost distance (LCD) model · Pedestrian evacuation · Walk time maps · Pedestrian evacuation analysis tool (PEAT)
1 Introduction

The world has been witnessing many destructive tsunamis over the past two decades (e.g., 2004 Indian Ocean, 2006 Java, 2007 Solomon Islands, 2009 Samoa, 2010 Chile, 2010 Sumatra, 2011 Tohoku, 2018 Sulawesi), causing a significant amount of life loss worldwide (NGDC 2012). Although those catastrophic tsunamis mainly occurred in the Pacific Ocean, historical records reveal that the coasts of Turkey experienced destructive tsunamis in the past (Ambraseys 1962; Soloviev et al. 2000; Fokaefs and Papadopoulos 2007; Ambraseys and Synolakis 2010; Altinok et al. 2011; Papadopoulos et al. 2012). There are various hazard assessment analyses conducted to model the tsunamiogenic sources based on the historical reports on the western coast of Turkey (Altinok et al. 2011; Salamon et al. 2007; Yolsal et al. 2007; Lorito et al. 2008; Yalciner et al. 2008; Okal et al. 2009; Basili et al. 2013; Sørensen et al. 2012; Papadopoulos et al. 2014). According to the seismic mechanisms of Hellenic and Cyprus arcs in the Eastern Mediterranean Sea, Yolsal et al. (2007) interpreted the tsunamiogenic hazard zones in the region. Lorito et al. (2008) portrayed the large set of seismic tsunamis generated by major fault zones in the Mediterranean Sea and concluded that not only distant but also local sources are needed to understand source-impact zones. Seismic tsunami sources that could create tsunami hazards in the Mediterranean and the Aegean Sea are also investigated by Yalciner et al. (2008). Okal et al. (2009) modeled the 1956 Amorgos tsunami triggered by an earthquake associated with extensional tectonics in the back-arc region of Hellenic subduction. According to the eyewitness reports, they concluded that the observed tsunami was incompatible with only seismic source and demonstrated both seismic and landslide source models. Basili et al. (2013) concluded that the impact of tsunamis generated by Mw = 7 earthquakes is expected to be strong at many localities in the Eastern Mediterranean Sea, depending on parametric fault characterization in terms of geometry, kinematics, and activity rates. Papadopoulos et al. (2014) provided tsunami hazard zones in the Mediterranean Sea and its connected seas based on various sources, including historical documents, geological signs, geomorphological imprints, observations from selected coastal sites, instrumental records, and eyewitnesses. Necmioglu and Ozel (2015) presented a comprehensive earthquake-generated tsunami hazard analysis for the Eastern Mediterranean, Aegean, and Black Seas through an extensive tsunami scenario database composed of 2415 scenarios. In addition to those studies displaying the possible tsunami sources in the Mediterranean Sea, two recent tsunami events striking the coasts of Turkey and Greece, Bodrum-Kos (20 July 2017, 20:31 UTC) and Izmir-Samos (30 October 2020, 12:51 UTC), have indicated once more that both countries should be prepared against tsunami hazards to mitigate the resultant damage and casualties (Dogan et al. 2019 and Dogan et al. 2021). Therefore, emergency managers, planners, and local decision-makers have recently sought mitigation strategies against destructive tsunami waves. Educating at-risk populations about what to do during a possible tsunami event and how to be prepared for such an event plays a vital role in tsunami risk reduction (NRC 2011; Tufekci-Enginar et al. 2021). Especially for the sudden-onset hazards like nearshore tsunamis, increasing awareness and evacuation planning is becoming the primary way to save lives as evacuees have only a few minutes to escape from the inundated zone towards the safety zone (NTHMP 2001; Tufekci-Enginar et al. 2021). Therefore, it is essential to estimate if the at-risk communities would have enough time for evacuation. Developing an optimal evacuation plan is a critical phenomenon for emergency managers and planners to assess the risk more accurately and realistically for vulnerable coastal communities to become more resilient (González-Riancho et al. 2013; Wang et al.
Instead of a specific scenario, evacuation maps should reflect a credible worst-case scenario (Walsh et al. 2000) or maximum hazard zone that summarizes multiple scenarios (Suleimani et al. 2002, 2010; Wilson et al. 2008; Nicolsky et al. 2011, 2013).

There have been several studies in literature focusing to understand whether or not at-risk populations have sufficient time to evacuate from hazard zone before the arrival of the first tsunami wave (Laghi and Cavalletti 2004; Jonkmann et al. 2008; Graehl 2009; Post et al. 2009; Yeh et al. 2009; Mas et al. 2012; Lovholt et al. 2012; Wood and Schmidtlein 2012, 2013; Fraser et al. 2014; Wang et al. 2016; Wang and Jia 2021; Celikbas 2022). In recent years, dynamic models (simulations, Agent-Based Models (ABM)) and static algorithms (shortest and quickest path, minimum cost network flow, Least-Cost Distance (LCD) models) have been used to model tsunami evacuation (Cheff et al. 2018).

ABMs are dynamic models that simulate individual’s behavior and their interaction during an evacuation from a specific tsunami scenario according to user-defined rules via mathematical equations and statistical analyses (Mas et al. 2012). Estimating human behavior during an evacuation, which is the primary goal of ABMs, is a highly complex issue that may change depending on the community’s preparedness and education level. However, due to coastal populations’ spatial and temporal variability, emergency managers mostly require evacuation time information independent of population exposure to be used in preparedness planning (Wood and Schmidtlein 2012). Instead of dynamic properties, LCD models calculate the shortest path for an evacuee to reach a safe zone from every location in a hazard zone via Geographic Information System (GIS) based on the static landscape properties (e.g., slope, land cover, road network) (Wood and Schmidtlein 2012).

In literature, LCD approaches to model pedestrian evacuation have become a growing topic (Laghi et al. 2006; Graehl 2009; Post et al. 2009; Wood and Schmidtlein 2012, 2013; Fraser et al. 2014; Celikbas 2022). LCD models examine pedestrian evacuation in various ways, from simple models based on only distance to safety from the hazard zone to more complex models that include the landscape properties (e.g., slope, land-cover, land-use, transportation network) affecting the walking pace of pedestrians. Post et al. (2009) increased LCD models’ complexity by including population density in the travel costs and considering the required time from the beginning of the tsunami warning. Lately, studies have focused on calculating travel costs, including the properties blocking the pedestrian evacuation to the LCD model, such as natural and structural barriers (e.g., rivers and fences), buildings, lakes, or high slopes. Travel costs might be calculated by either cost distance algorithms (isotropic cost distance) or path distance algorithms (anisotropic cost distance). Cost distance algorithms calculate the straight distance between every cell in the hazard zone to the safety, whereas path distance ones (anisotropic cost distance) calculate actual trigonometric distances between various elevation points. Wood and Schmidtlein (2012) made a sensitivity analysis of LCD models to elevation and landcover data, where they concluded that anisotropic cost distance models estimate travel times more realistic than isotropic ones. Lately, anisotropic LCD models have been preferred to calculate evacuation times by path distance algorithms for self-initiated pedestrian evacuation from sudden-onset hazards such as tsunamis, debris flows, volcanic mudflows, and flash floods (Wood and Schmidtlein 2012, 2013 and Fraser et al. 2014).

The current study focuses on the spatial distribution of evacuation times via the LCD approach rather than understanding individual’s behaviors and interactions during an evacuation. The research is also interested in understanding the difficulties of movement across the landscape during the evacuation process while considering the real-world evacuation conditions that affect pedestrian movement like landscape characteristics. The results
reveal the individuals within the danger zone (hazard zone-inundated or flooded area) could evacuate before tsunami waves arrive on the land, which provides valuable information for local emergency managers.

This study is representing a part of the ‘Tsunami Last Mile’ project (Necmioğlu et al. 2019) conceived and organized by the JRC with funding from the European Commission Department for Civil Protection and Humanitarian Aid Operations (DG ECHO). The project was conducted by the joint team of Remote Sensing and GIS Laboratory of the Department of Geological Engineering and Ocean Engineering Research Center of the Department of Civil Engineering of Middle East Technical University. Bodrum district of Muğla, Turkey is one the pilot areas where the ‘Tsunami Last Mile’ project was implemented.

The part of the project represented here aims to prepare pedestrian tsunami evacuation time maps for the southern coasts of the Bodrum peninsula, to provide a base point for emergency managers and local decision-makers during emergency planning. In coherence with this scope, to estimate spatial evacuation time distribution within the hazard zone, anisotropic LCD modeling via PEAT (Jones et al. 2014) is calculated and results are verified in the field (Celikbas 2022).

One of the tasks of ‘Tsunami Last Mile’ project was determination of where critical tsunami scenarios for the region and modeling those scenarios using tsunami numerical tool NAMI DANCE (Necmioğlu et al. 2019). The determined critical scenarios were composed of five seismic (365-Crete, 1303-Eastern Mediterranean, 1956-Amorgos, Gokova and Gulluk Bay), two submarine landslides (Amorgos and Gokova-North-Datca), and two earthquake-triggered submarine landslide scenarios (Celikbas 2022). For the current manuscript, the tsunami modeling results of 1956-Amorgos seismic and combine Gokova seismic and North Datca landslide critical scenarios are used as the worst-case scenarios, since those scenarios are the ones that causes more inundation on land at selected study areas on the southern coasts of the Bodrum peninsula. According to the selected worst-case scenarios, the earliest arrival time of the first wave to the study areas is determined to be 9.6 min among all of the critical scenarios (Celikbas 2022). Inundation maps derived from those scenarios are used in the determination of the hazard zones to generate pedestrian tsunami evacuation time maps.

2 Study area

The study area for the tsunami evacuation model is the southern coast of Bodrum Peninsula (Fig. 1). Bodrum is a district of Muğla province, located in the southwest of the Aegean Region of Turkey and coasts to the eastern Mediterranean Sea, a worldwide touristic center, hosting popular hotels with long and famous beaches, historical and touristic places. The population is 181,541 (TUIK 2020), which increases to more than a million during the summer months as its economic livelihood is mainly tourism (Erdogan 2016).

The Mediterranean Sea hosts active faults and zones that can create earthquakes and tsunamis (Lorito et al. 2008; Tiryakioglu et al. 2018). Bodrum Peninsula lies on the Northern side of the Gulf of Gokova, a seismically active region of the Alpine-Himalayan belt, formed by the North–South-directed extensional regime of Western Anatolia (Dewey and Şengör 1979). Bodrum Peninsula and the Gulf of Gokova region are western Turkey’s most seismically active areas, where earthquake swarms occurred (Kalafat and Horasan 2012). Gokova Fault Zone, the most active fault in Southwest Anatolia where the epicenters of earthquakes are concentrated, is extended to the north of the gulf and separated into several
second-order submarine faults (Tiryakioğlu et al. 2018). Ocakoğlu et al. (2018) found a good correlation between the region’s general seismicity and the focal mechanism solutions of the 20 July 2017 Bodrum-Kos earthquake. This earthquake generated a tsunami affecting the southern coasts of the Bodrum Peninsula with a maximum runup of 1.9 m (Dogan et al. 2019).

3 Pedestrian evacuation modeling via PEAT

The time required for a pedestrian to reach out of the hazard zone based on an LCD model is implemented in the GIS software of ESRI’s ArcMap (Wood and Schmidtlein 2012, 2013; Jones et al. 2014). The Pedestrian Evacuation Analyst Tool (PEAT) used in this study considers the difficulties of pedestrian movement within a hazard zone (cost distance) based on the static landscape properties such as slope and land-cover types. PEAT was developed by Jones et al. (2014) with the USGS support as a decision support system for studies on self-initiated pedestrian evacuation against sudden-onset hazards like tsunamis, lahars, and flash floods. It calculates the required evacuation time by considering an anisotropic path distance model where the difficulty of the direction of travel against a slope is incorporated. However, PEAT does not consider possible crowd behavior, such as panic and chaos, which may affect the time required for evacuation. The anisotropic LCD model uses cost distance geoprocessing that also includes the influence of land cover types (Laghi et al. 2006; Post et al. 2009). Land cover and elevation-derived slope data are converted to speed conservation values (SCVs), representing maximum travel speeds expected in areas with
given conditions (Wood and Schmidtlein 2012). Generating evacuation time maps in PEAT requires two main processes: preprocessing input data (DEM, land-use/land-cover, hazard zone, and safe zone) and creating respective evacuation surfaces (Jones et al. 2014).

3.1 Data acquisition and assumptions made in the study

The databases used for the analysis of this study are mainly created with the datasets acquired from Bodrum Municipality within the scope of the Last Mile project (Necmioğlu et al. 2019). A high resolution (5 m) DEM and land cover/land use vector dataset of Bodrum Peninsula is generated with datasets obtained from various local sources and enhanced with the dataset provided by Bodrum Municipality (Fig. 2). In addition, open-source data from Open Street Map (OSM) and Google Earth Images are used for the cases that require modifications due to inconsistency or deficiency of the provided data.

All available evacuations models, either ABM or LCD-based, and their applications in the literature, use assumptions for generalizing information about individual’s behaviors, landscape properties, or creating a hazard zone. Along the analysis of this study, a set of assumptions is made both on tsunami modeling and evacuation modeling. The assumptions made through this study are listed below:

- Tsunami numerical simulations are performed according to the mean sea level. Tide or a storm condition is not considered.
- All man-made structures are assumed to be non-damaged after the earthquake and tsunami. The impact of a collapsed building or a road closure is not considered.

![Digital Elevation Model (DEM) used in the study](image)
• It is assumed that the tsunami inundation is composed of only water and does not carry any debris material.
• The impact of a possible crowd behavior, such as panic and chaos, has not been taken into consideration during the evacuation.
• Although rivers are considered as obstacles while creating the evacuation time maps, other features that can interrupt the evacuation process (such as fences or walls) are not considered due to the data scarcity.

3.2 Preprocessing of data

3.2.1 Digital elevation model (DEM) and slope

In the first stage of PEAT, high-resolution DEM (Fig. 2) and its derivative (slope map) are used. Since the search direction of the Path Distance Tool of PEAT is opposite of the direction of evacuation, downhill in the algorithm means uphill for an evacuee. The slope direction is inverted since the LCD calculations of PEAT begin from the safety and expand towards the hazard zone. Various researchers have used different slope-walking speed relationships in literature (Butler et al. 2000; Post et al. 2009; Graehl 2009; Anguelova et al. 2010). In this study, SCVs are based on Tobler’s (1993) hiking function, which explains the relationship between topographic slope values and the walking speed of a pedestrian (Wood and Schmidtlein 2012).

3.2.2 Land-cover/Land-use

Land-cover/Land-use data are composed of a base layer and ancillary layers to satisfy PEAT requirements. The base layer represents the spatial distribution of Earth’s coverage of study areas, affecting pedestrians’ walking pace during an evacuation, such as beaches, cultivated lands, and bushes. Several studies have been conducted to classify land-cover layers into SCV surfaces (Laghi et al. 2006; Post et al. 2009; Anguelova et al. 2010). However, in this study, SCVs of each land-cover type are formed with the information provided by Wood and Schmidtlein (2012). Once a composite land cover vector data is created, SCVs are assigned to each type of data (Table 1) based on the energy cost terrain coefficients defined by Soule and Goldman (1972). Among all the land cover types in base layer, developed highly-populated areas provide pedestrians with an easy way for vertical and horizontal evacuation due to the proximity to buildings and roads; hence its SCV has the highest value of 0.9091. On the other hand, beaches with unconsolidated sand where it is hard to walk, have the lowest SCV.

| Table 1 | Speed conservation values of the land-cover types (Wood and Schmidtlein 2012) |
|---------|-------------------------------------------------|
|         | Land-cover type                        | Speed conservation value (SCV) |
| Base layer | Developed- highly populated | 0.9091   |
|          | Cultivated crops             | 0.8333   |
|          | Bush                        | 0.8333   |
|          | Beach                       | 0.5556   |
| Ancillary layers | Roads        | 1        |
|          | Rivers                      | 0        |
Cultivated crops and bushes are the landcover types where walking through them for evacuation is more convenient than beaches; therefore, 0.8333 is assigned.

In addition to the base layer, any layer that makes pedestrian evacuation easier, harder, or blocking is considered as ancillary layers, such as roads, fences, buildings, and water bodies (Wood and Schmidtlein 2012). Roads are the primary pathways for pedestrians to evacuate in the easiest and fastest way, whereas any water body can abruptly block the evacuation (such as rivers or lakes), of which both are included as ancillary layers (Fig. 3). Therefore, SCV varies from 0, meaning no evacuation possible like rivers, to 1, such as roads providing the most suitable surface for pedestrians (Table 1). The SCV will then be used as a source to create the cost-inverse raster of different land-cover types in PEAT.

### 3.2.3 Hazard zone/Safe zone

Figure 4 shows the maximum flow depth distribution maps for the five selected study area. Hazard zones are defined as inundated areas on land from the credible worst-case scenarios resulted in tsunami modelling performed in NAMI DANCE. PEAT uses resultant hazard zones as input to create a safety zone for pedestrians to evacuate. To define the safe zones, raster flow depth results (hazard zone) are vectorized and subtracted from study area vector. Validations of safe zones are done by removing excessive sliver polygons and safe zone islands within the inundated hazard zones.

### 3.2.4 Resultant evacuation walk time surfaces

The path distance surface is generated using the Path Distance Geoprocessing Tool (ESRI 2009) that calculates the cost distance according to elevation and land-cover/land-use SCVs. The evacuation time surface is calculated by dividing the path-distance surface with recommended walking speed of the evacuee assigned according to crosswalk walking standards in the United States as a slow walking pace (1.1 m/s) (Wood and Schmidtlein 2012).

The evacuation time maps are produced for five selected areas, Central Bodrum, Gumbet, Yahsi, Akyarlar-Karaincir-Aspat, and Bitez Bays (Fig. 5). The resultant evacuation time maps show the time zones for evacuees with a 1 min increment except for the first increment (0.5 min). As a result of our study, the longest time required for evacuees to get out of the hazard zone with 1.1 m/s walking speed from the tip of Bodrum Marina’s breakwater is calculated as 8 min (Fig. 5a). However, in the absence of breakwater, the travel time is calculated as 4 min from the Aganlar Shipyard & Marina. As it is expected, famous beaches located at the Bodrum, like Gumbet Beach (3 min), Camel Beach (6 min) located in Yahsi Bay, Aspat Beach (5 min), Karaincir Municipal Beach (5 min), have the longest evacuation time since they are the places having maximum inundation distances (Fig. 5b–d).

### 4 Discussion

Successful evacuation planning is critical for emergency managers and local decision-makers to save lives from potential future tsunamis. Therefore, creation of evacuation time maps based on critical hazard scenarios provide a substantial information to build an effective evacuation plan.

The resultant evacuation walk time maps (Fig. 5) reveals that, among the selected areas, the maximum time required for evacuees to get out of the hazard zone with 1.1 m/s walking
Fig. 3 The land-cover/Land-use map composed of beaches, cultivated crops, bushes, and additional road and river ancillary layers for a. Central Bodrum, b Gumbet Bay, c Yahşi Bay, d Akyarlar-Karaincir-Aspat Bays, e Bitez Bay
Fig. 4 Flow depth maps used as hazard inputs for PEAT (Necmioğlu et al. 2019, Celikbas 2022) a Central Bodrum, b Gumbet Bay, c Yahsi Bay, d Akyarlar-Karaincir-Aspat Bays, e Bitez Bay
Fig. 5 Tsunami Evacuation Walk Time Map for a. Central Bodrum, b. Gumbet Bay, c. Yahsi Bay, d. Akyarlar-Karaincır-Aspat Bays, e. Bitez Bay
speed is 8 min. This provides enough time for individuals to reach safety since the arrival
time of the first tsunami wave (9.6 min) is higher than the maximum calculated evacuation
time required.

This study uses, tsunami numerical simulation results that are performed according to
the present mean sea level; however, actual sea level continuously changes due to tides or
storms, hence for different seasons, lunar cycles, sea level fluctuations and climatic changes
a sensitivity analysis should be made followed by a multitemporal evacuation analysis.

The earthquake’s impact on buildings, roads, bridges, or any structure is neglected,
which may slow the evacuation dramatically, or even preclude at certain evacuation routes.
Additionally, all the buildings are assumed to be non-damaged by the tsunami waves. How-
ever, in coastal resorts like Bodrum, there are lots of unstructured temporal buildings, shel-
ters, etc., that might be vulnerable to earthquakes. In the case of a strong earthquake, rein-
forced concrete buildings may collapse along with unstructured ones towards the important
roads, which may block the evacuation suddenly and cause congestion. Although, in PEAT,
roads are assumed as the safest places to evacuate for an individual, in addition to the col-
lapse of buildings blocking the roads, the road network itself might be destroyed by ground
deforations caused by earthquakes.

The inundation is assumed as composed of only water, excluding the debris material,
during the numerical simulations. However, the damage observed is mostly due to the
debris materials carried by tsunami waves, such as boats, cars, parts of trees, and concrete
blocks detached from the ground or houses.

The LCD-based evacuation models consider the movement of a pedestrian based on
landscape properties, however, they ignore the individual’s behaviors and interactions dur-
ing an evacuation. In contrast, ABMs assess hundreds of individuals’ decisions and their
interactions based on a set of rules (Wang et al. 2016). Understanding and modelling indi-
vidual decision-making behavior during a panic situation like evacuation is a very complex
phenomenon, which depends on the different awareness or preparedness of all individu-
als which may also affected by near experiences and ancestral knowledge in that region
(Tufekci-Enginar et al. 2021). Possible different evacuation behaviors depending on indi-
vidual awareness or preparedness and the effect of possible crowd behavior, such as panic
and chaos, is not taken into consideration in the LCD model (Liu et al. 2018).

LCD models ignore congestion of roads leading to panic among evacuees that causes
prolonging of the required evacuation time. Depending on the roads’ congestion level,
evacuees’ travel speed may vary; however, in LCD models, it is assumed that all individu-
als in a community have the same and constant speed of evacuation (Wood and Schmidtlein
2012). There is no information on the human capacity in the available road dataset, which
is essential to prevent congestions during an evacuation.

The routes in docks and breakwaters are structures where evacuation is difficult since
there is only one narrow path to reach the safe zone (Wood and Peters 2015). Although it
does not reflect the reality, it is assumed that all the roads have identical SCVs providing
the easiest way for a pedestrian.

Evacuation process for tsunamis requires an official warning if there isn’t any natural
warning felt by the people such as an earthquake or the necessary awareness to observe
the silent warnings such as receding of the sea. In that case, the tsunami warning system’s
reaction time, should also be considered, including the institutional notification and the
decision time to notify the at-risk community (Post et al. 2009).

PEAT requires lots of complex data representing landscape properties that affect pedes-
trians’ walking pace during an evacuation, such as slope, barriers, roads, or water bodies
located within the hazard zone (Wood and Schmidtlein 2013). Due to data scarcity and
resolution-based constraints, in this study, only the rivers in the study areas are included as the elements that would act as obstacles (with SCV of 0). However, in the case of available higher resolution and more detailed datasets, barriers such as fences or walls could be included, which would improve resultant evacuation walk time maps.

In order to create successful evacuation planning, the data must be accurate, up-to-date, and with high resolution. Since the shoreline of Bodrum is continually changing and developing due to the construction of new coastal facilities such as marinas, renewed buildings, constructions of new buildings like hotels and roads, the data used for the LCD models should be updated regularly to avoid misleading an evacuee.

Bodrum is one of Turkey’s largest holiday towns and also attracts many tourists from abroad; hence the population rises to ~2 million people in the summer seasons (Erdogan 2016). The spatial distribution of the population is time-dependent and changes dramatically based on seasons. Since the occurrence time of a tsunami cannot be estimated, the detailed dataset that should represent the spatial distribution of population both in summer and winter seasons should be included in the evacuation plans. In addition to seasonal changes, population changes during the day and the night should be considered.

4.1 Validation of resultant evacuation time surfaces

The resolution of input data for PEAT totally affects the interpretation of resultant tsunami evacuation maps (Fig. 5) by an individual during an evacuation. According to the model sensitivity analysis conducted by Wood and Schmidtlein (2012), PEAT tended to underestimate the required evacuation time with coarser-resolution elevation data. Therefore, DEM resolution plays a critical role in the resultant maps and validation is required to make sure accuracy of resultant evacuation time maps (Fig. 5). For this purpose, three different locations having maximum evacuation time to reach the safe zone and their shortest path to reach the safe zone are selected as validation routes (Figs. 6, 7, 8). While choosing the validation routes, it was prioritized that the route starts from a location that has a high value in the evacuation walk time surface maps and wide enough to provide the easiest evacuation for pedestrians. The validation is performed by a nearly constant speed not exceeding 1.1 m/s. During the walk, actual time and distances are recorded (Table 2). The time calculated by PEAT in the final resultant evacuation time maps at the locations where the validation route starts (Figs. 6, 7, 8) is compared with the time passed to reach the safe zone during the walk (Table 2).

According to validation results (Table 2), for three of validation routes (Gumbet, Bitez and Yahsi), measured time to reach the safe zone is lower than it is calculated by PEAT. Therefore, for those three routes (Figs. 6, 7, 8), evacuation is possible with 1.1 m/s speed according to the proposed evacuation time of PEAT.

5 Conclusion

The necessary baseline study on tsunami evacuation modeling is constructed for emergency managers and local decision-makers. The geospatial distribution of pedestrian evacuation time was calculated via PEAT (Jones et al. 2014), one of the LCD models, for highly populated coastal areas of Bodrum Peninsula; Central Bodrum, Gumbet Bay, Bitez Bay, Yahsi Bay, and Akyarlar-Karaincir-Aspat Bays. The hazard zones used in PEAT are obtained from resultant worst-case scenarios where the numerical simulations
performed via the NAMI DANCE model (Necmioğlu et al. 2019; Celikbas 2022). The tool considers the SCVs representing the relationship between walking speed and
landscape properties such as slope and land-cover/land-use. In this study, a slow walk walking speed (1.1 m/s) is taken in the calculations.

The final resultant maps reveal the spatial distribution of time required for a person to reach a safe zone. According to evacuation walk time maps (Fig. 5), the longest evacuation times are 8, 6, 5, 4, and 3 min for Central Bodrum, Yahsi, Akyarlar-Karaincir-Aspat Bays, Bitez, and Gumbet bays, respectively. The maps were validated via fieldwork on three selected routes by performing on foot evacuation with a constant desired speed. The prepared evacuation walk time maps provide a solid base for emergency managers, planners, and local decision-makers to make decisions on the locations of tsunami evacuation routes, emergency assembly areas or vertical evacuation structures.

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Declarations

Conflicts of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Data availability The data used in this study are provided by Bodrum Municipality and acquired from open sources (Google Earth Images and Open Street Maps).

Code availability Pedestrian Evacuation Analyst Tool, developed by USGS for ArcGIS 10.5, is used in the study during calculations. (available at; https://www.usgs.gov/software/pedestrian-evacuation-analyst-tool).

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