



# Geospatial mapping of Tsunami susceptibility of Karachi to Gwadar coastal area of Pakistan

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## Abstract

The coastal area holds great importance as it sustains a large number of people in addition to various bio-networks that have economic as well as biological significance. However, these may be prone to environmental calamities such as tsunamis. In the coastal areas of Pakistan, numerous earthquakes have been triggered by the tectonic movement under the Indian Ocean. Karachi and Gwadar cities being the economic hub of the country is at the potential risk of tsunamis; therefore, multi-criteria GIS mapping of tsunami susceptibility has been conducted in this paper for the Karachi to Gwadar, the coastal area of Pakistan. This study includes many geospatial variables such as coastal proximity and shape, topographic elevation and slope, and topography relative to the direction of the tsunami. Analytic hierarchy process (AHP) is exercised to develop an order of weights for each geospatial variable. For the potential tsunami risk, a land use map of coastal area of Pakistan is overlaid on the tsunami susceptibility map, and the final output map has shown that residential buildings, commercial complexes, and agricultural areas are vulnerable to destruction. Studies involving GIS are helpful in the evaluation of disaster, thereby aiding in the acceleration of local forecasting for the management of natural catastrophes like tsunamis. Tsunami susceptibility map presented in this paper seeks to support the evidence of the occurrence of the tsunami and the efforts directed towards the management of tsunami in the coastal areas of Pakistan.

**Keywords** Tectonic movement · Earthquakes · Tsunamis · Geographical information system (GIS) · Analytic hierarchy process (AHP)

## Introduction

Coastal zones comprise about 4% of the earth's surface and consist of about one-third of the world's population. Conferring to an estimate of the United Nations Environment Program (UNEP), World Conservation

Monitoring Centre, published in 2006, within fifteen years, the coastal zones are anticipated to have a double amount of population (Jaffe and Gelfenbuam 2009; Wijetunge 2009). Additionally, the coastal areas of the world have diverse ecologies of high biotic and fiscal significance. It is because coastal areas contain mangrove forests, lagoons, seagrass beds, coral reefs, dunes, and other coastal vegetation (Srinivasalu et al. 2007; Yan and Tang 2009). This ecosystem might be exposed to natural disasters like tsunamis. The ongoing seismic activity might affect Pakistan and can trigger a tsunami in this region. In the contemporary one hundred years from 1915 to 2015, around 100 considerable earthquakes have struck Pakistan (Irtem et al. 2009).

It is revealed that the majority of the tsunamis at coastal line of Pakistan have occurred as a result of tectonic activity in the Makran region and alongside the divergent boundaries of Indo-Australian tectonic plates. Based on historical records, a wide range of coastal areas of Pakistan including Makran, Gwadar, Badin, and Karachi are predicted to be vulnerable to tsunami danger. Several studies have been conducted on

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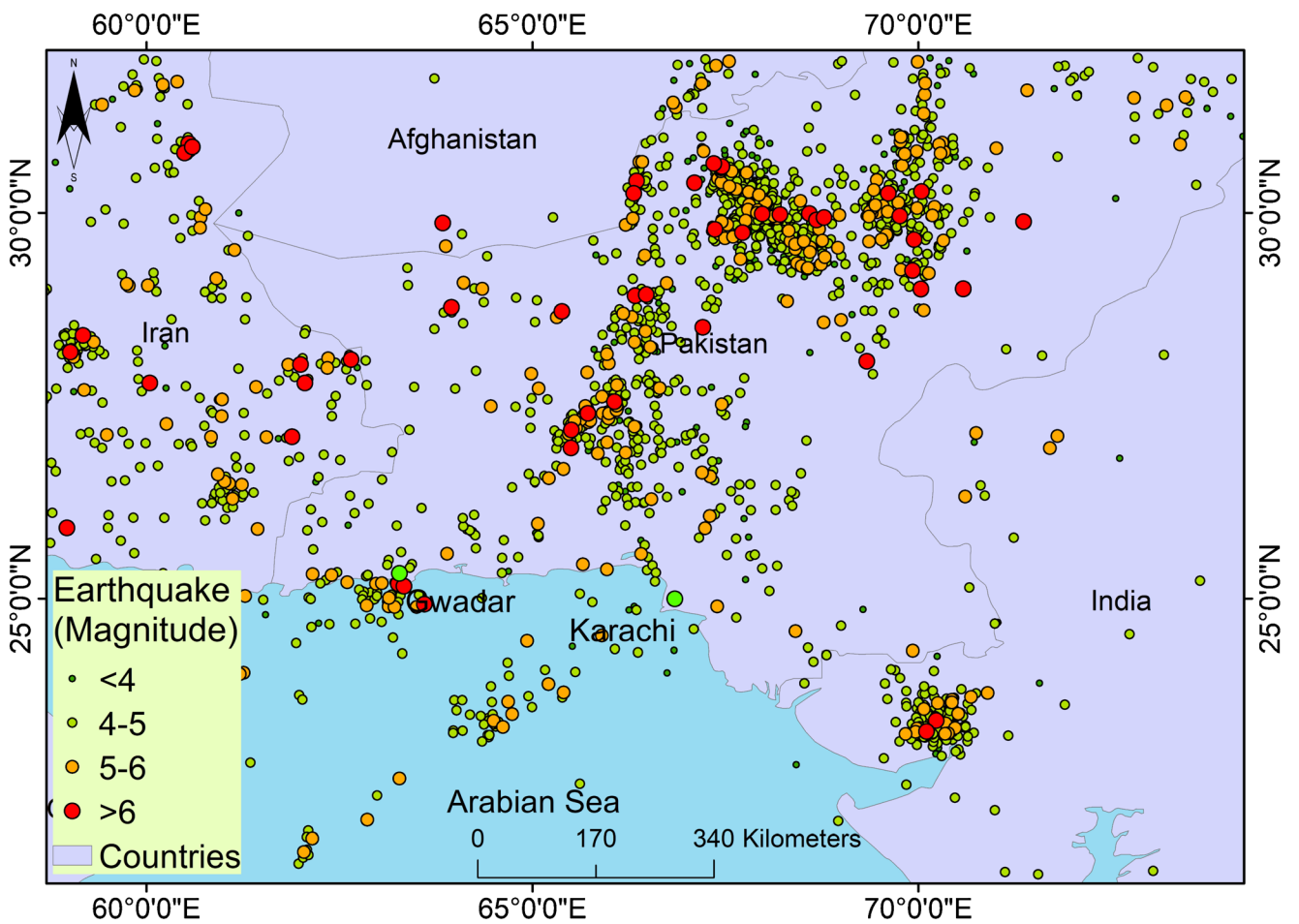
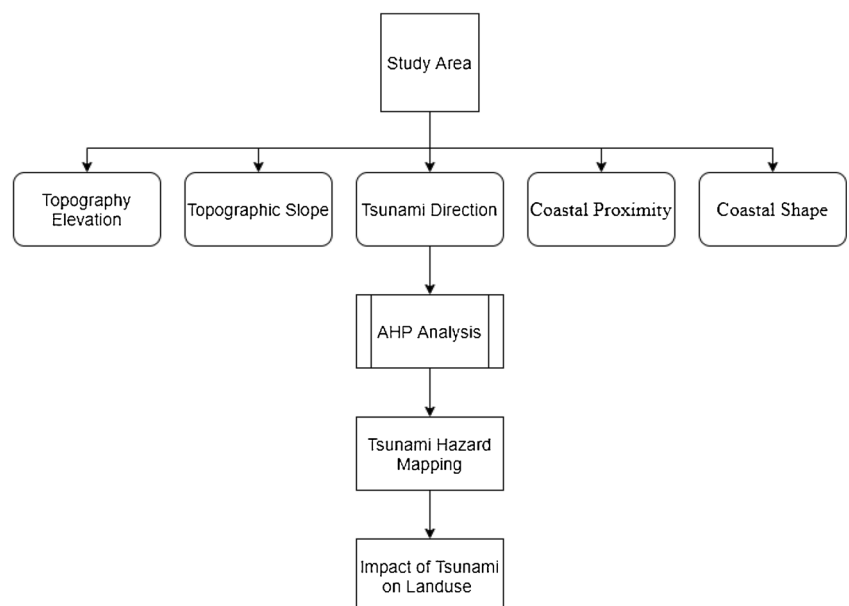


Fig. 1 Earthquake recorded (1950–2019) in the Arabian Sea and its surroundings

Fig. 2 Methodology flowchart



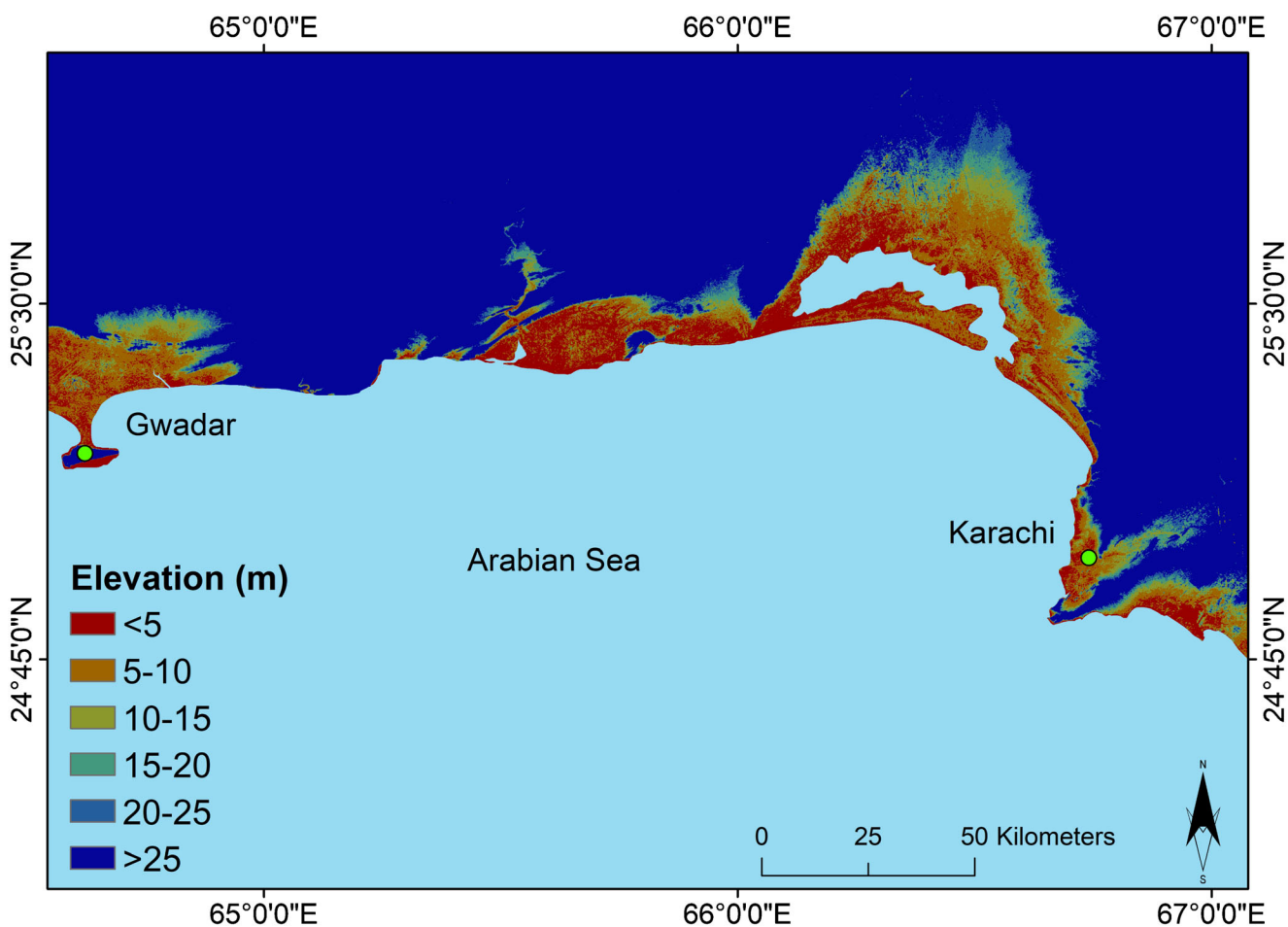
**Table 1** Topography elevation susceptible classes

Elevation (m)	Susceptibility
< 5	Very high
5–10	High
10–15	Medium
15–20	Low
20–25	Very low
> 25	No effect

tsunami propagation modeling, geomorphologic changes caused by the tsunami, and effect of the tsunami on the natural environment besides ecological defense mechanisms against tsunami impairment (Kathiresan and Rajendran 2005; Cocharda et al. 2008). In 2004, the befallen Tsunami that occurred in the Indian Ocean is placed among the disastrous tsunamis, and the area wise spread was very large scale resulting in 163,978 casualties.

Latest studies have used weighted mean to examine tsunami susceptibility by evaluating various variables and

developing a susceptibility index that can control tsunami destruction as in utmost situations; the weighting method was rather prejudiced and was centered on the somewhat non-scientific procedure (Papathoma et al. 2003; Papathoma and Dominey-Howes 2003; Dominey-Howes and Papathoma 2007; Dominey-Howes et al. 2009; Omira et al. 2009). Alternatively, the analytic hierarchy process (AHP) has been exercised by Dall’Osso et al. (2009) as an extra appropriate weighting practice. However, this investigation involves a moderate analysis of tsunami proneness, whereas this paper involves a multi-criteria evaluation GIS-based approach for tsunami susceptibility for the Karachi to Gwadar coast area of Pakistan. In this study, different geospatial variables like topography and tsunami direction besides coastal proximity and shape are taken into consideration. Past research analyzed physical features such as structures, but in the current study, the regional environmental features are taken into consideration to produce a tsunami susceptibility map of a 30-m grid. The weighting scheme has been designed for the application of the AHP (analytical hierarchy process) technique.



**Fig. 3** Susceptibility in terms of topographic elevation

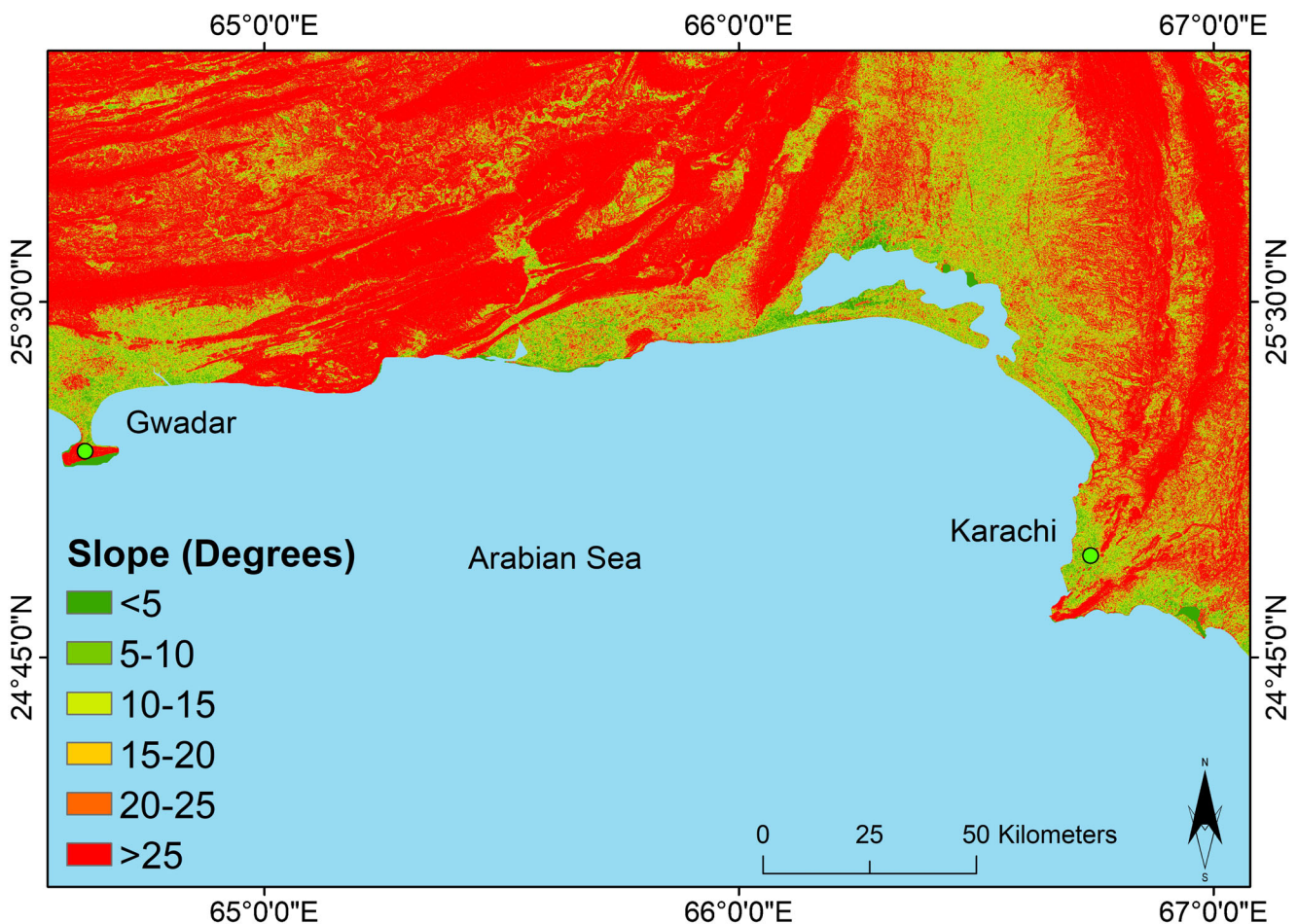
**Table 2** Topographic slope susceptible classes

Topographic slope (%)	Susceptibility
0–5	Very high
5–10	High
10–15	Medium
15–20	Low
> 20	Very low

### Tectonic setting of the study area

Karachi is one of the major metropolitan cities of Pakistan, situated at 24°51' N and 67°02' E. It enjoys an undeniable status of being the economic hub of Pakistan and therefore harbors a large proportion of the economic activity of the country. With a population of about 23.5 million (according to 2013 census) and comprising of an area of approximately 3527 km<sup>2</sup> or 1362 mi<sup>2</sup>, Karachi exhibits a concentration of above 6000 individuals each square kilometer. Similarly, Gwadar is also another major city at the coast of

Pakistan which is developing as an economical hub for the future. Southeast Asia consists of a tectonically vigorous area. Down the shorelines in Pakistan as well as India, tsunamis are, although less common, not entirely rare or unheard of. A detailed review of the geological history including the modern time reveals the occurrence of tsunamis and deep-sea earthquakes at different times, throughout history in the North Arabian Sea. This is indicated in Fig. 1. However, among these events, very few have been considered and recognized, effectively. In India's western region, devastating tsunamis occurred as a consequence of earthquakes, in 1524 and then again in the year 1819, in the Kutch area. Several earthquakes, occurring in the past hundred years, point towards the seismically active nature of the region (Fig. 1). In Pakistan, down the Makran coasts' subduction zone, massive earthquakes have given rise to destructive tsunamis. Although the very little record is present to support this supposition, it is believed that tsunamis like these were extremely violent and massive in the coastal areas of Pakistan, India,



**Fig. 4** Susceptibility in terms of topographic slope

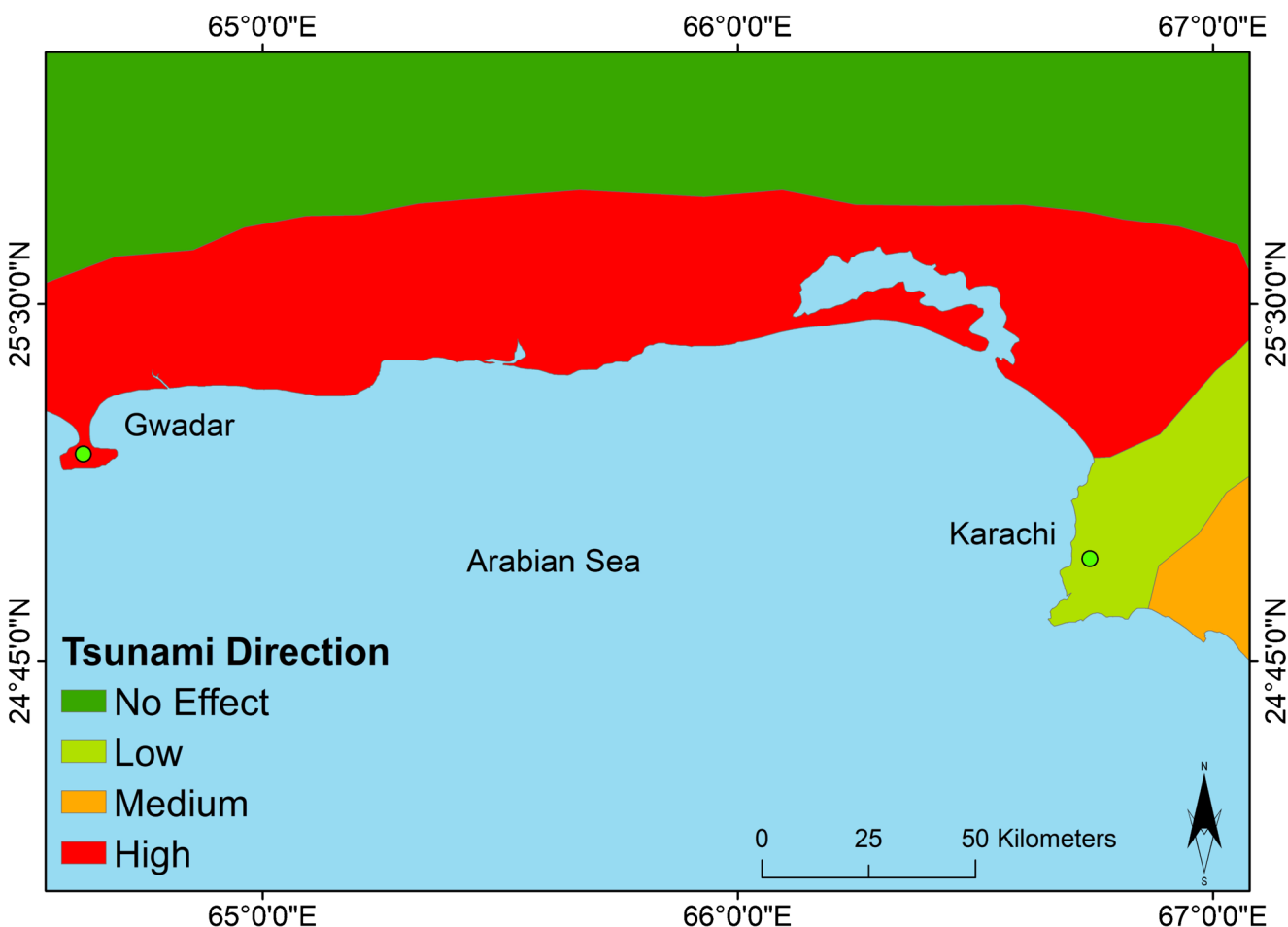


**Table 3** Tsunami direction susceptible classes

Tsunami Direction	Susceptibility
Perpendicular	High
Oblique	Medium
Covered	Low

Iran, and Oman. These tsunamis enormously affected the countries and islands lying on the borders of the Indian Ocean. One of the most significant earthquakes leading to a tsunami that resulted in massive destruction and human casualties was that of 28 November 1945. The run-up height for this tsunami varied between 1 and 13 m. Probably, the earliest known tsunami in this region was one that occurred as a result of a large magnitude earthquake that took place in 326 B.C in the Indus delta (Murty and Bapat 1999). In the Arabian Sea, this earthquake caused a tsunami and destroyed Alexander’s Macedonian caravan during their journey back to Greece later the

Indian invasion as says the literature. The studies prove that Pakistan’s coastlines are highly susceptible to massive earthquakes leading to violent tsunamis. Makran coast is one such earthquake-prone region as indicated in Fig. 1. Keeping in view, the seismic activity that took place in recent years, it would not be wrong to predict that a large magnitude earthquake might take place in the area lying west of the area of the event of 1945 (Jacob and Quittmeyer 1978). An earthquake of this kind could lead to a damaging tsunami. Pakistan coast lies in front of both the Arabian Sea and the rift point of Australian and Eurasian tectonic plates. Therefore, in case of an event of these rifts becoming active, cities like Karachi and Gwadar might face enormous destruction. Looking back, into the past, it can be observed that earthquakes of very high magnitudes and intensity have occurred in this region, and in the future, such high magnitude earthquakes might be anticipated in this area. In this context, to help ineffective management and dealing with possible and anticipated calamities, an approximation of vulnerability to a tsunami



**Fig. 5** Susceptibility in terms of tsunami direction

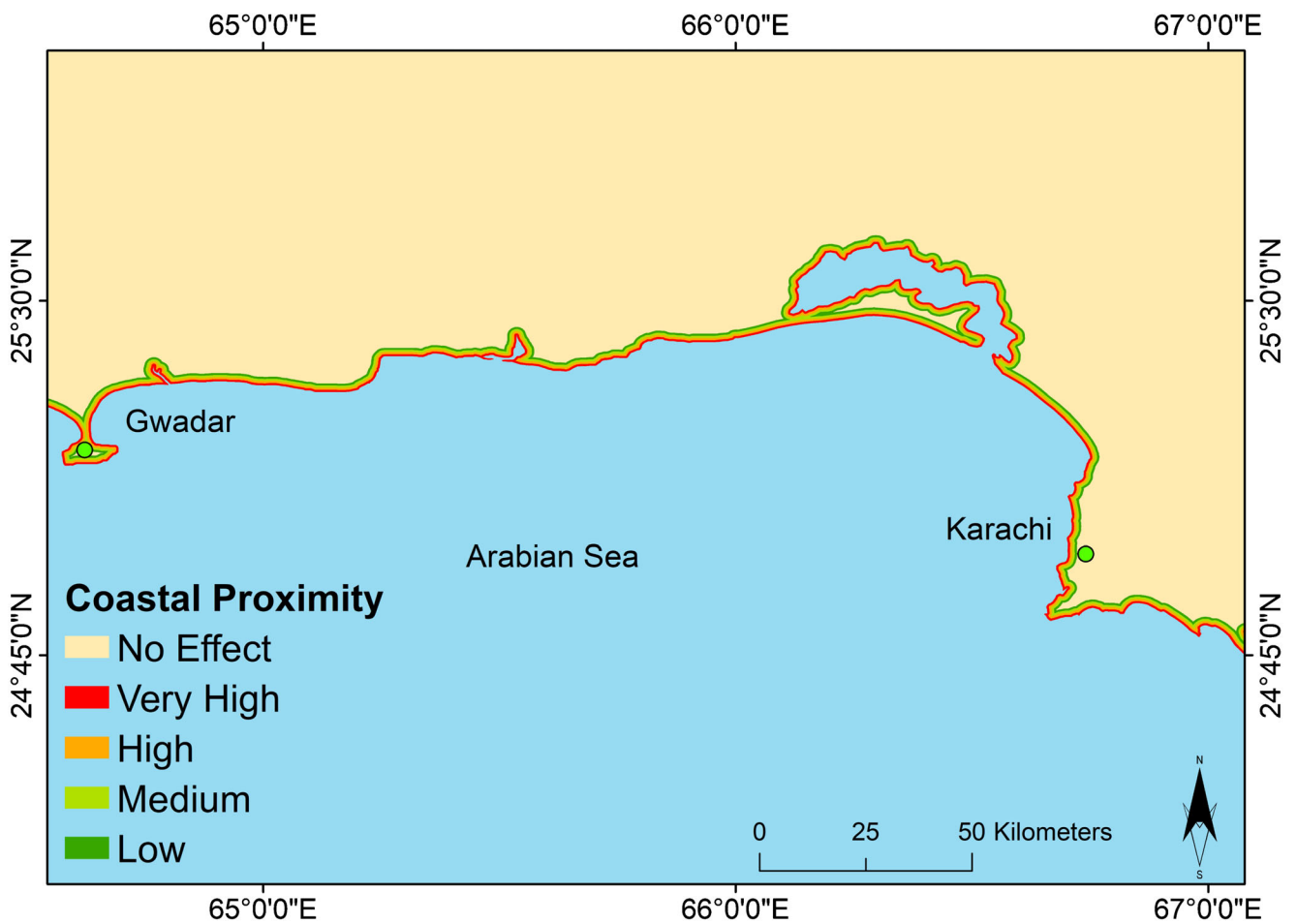


Fig. 6 Susceptibility in terms of coastal proximity

with the respective environmental physiognomies can play a beneficial role.

### Methodology

After extensive literature review, a detailed methodology has been revised in which five probables which may influence the Tsunami hazard are considered for the hazard assessment. These five parameters are topographic elevation, topographic

slope, coastal shape, coastal proximity, and tsunami direction. Once these parameters were finalized, all these parameters were ranked with the help of analytical hierarchy technique (AHP). After calculating the weightages of each dataset, tsunami hazard was computed using weighted overly function. Then at the end, tsunami hazard was correlated with the land use of the area to identify the probable danger to the land. Detailed methodology of each step and classification is explained in the “Result” section. Figure 2 shows the methodology flowchart adopted in this study. Methodology of this research is adopted from Aslam et al. (2017) and Sinaga et al. (2011).

Table 4 Coastal proximity susceptible classes

Distance (m) from shoreline	Susceptibility
0–100	Very high
100–200	High
200–300	Medium
300–400	Low
> 400	No effect

Table 5 Coastal Shape susceptible classes

Coastal Shape	Susceptibility
Gulf	Very high
Straight coast	Medium
Cape	Low

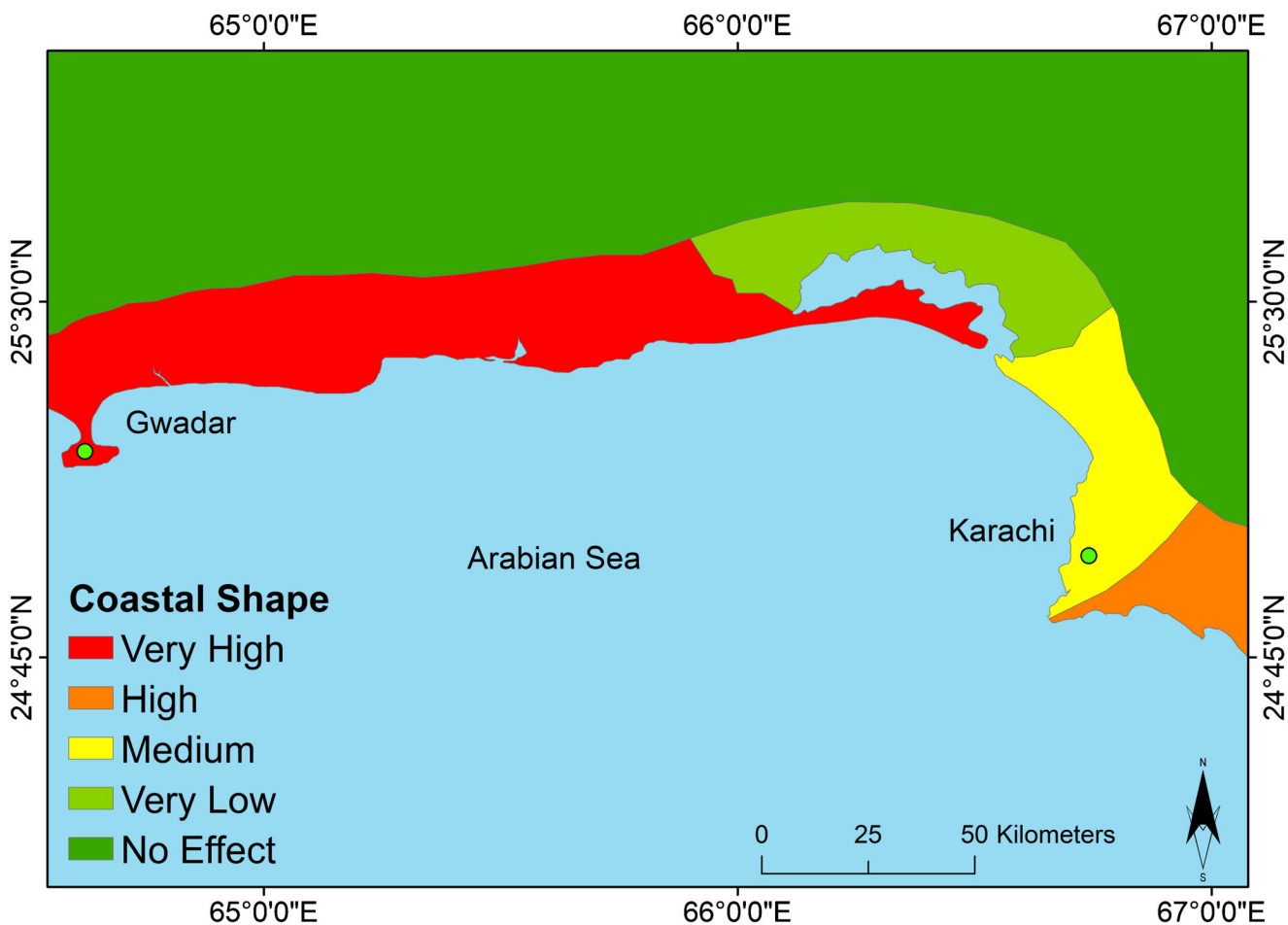


Fig. 7 Susceptibility in terms of coastal shape

Analytical hierarchical process (AHP) is utilized for investigating and mapping the tsunami hazard. To identify the importance of each factor AHP, a pairwise correlation was utilized by allotting numerical value through investigation of related factors (Althuwaynee et al. 2014). The procedure of AHP is classified into three steps which include identification of a hierarchy of objectives, pairwise comparison of criteria, and then weightages calculations for all datasets.

**Results**

**Topographic elevation**

In the evaluation of an area’s susceptibility to the tsunami, a basic and significant parameter is the topographic elevation. To find out the topographic elevations of the area under study, the digital elevation model (DEM) has been determined by

Table 6 AHP comparison matrix (Aslam et al. 2017)

Categories	Topographic elevation	Topographic slope	Tsunami direction	Coastal proximity	Coastal shape
Topographic Elevation	1	3	0.5	3	3
Topographic Slope	0.333333	1	2	3	2
Tsunami Direction	2	0.5	1	2	3
Coastal Proximity	0.333333	0.333333	0.5	1	0.5
Coastal Shape	0.333333	0.5	0.333333	2	1
Weight	0.3092	0.2392	0.2666	0.0809	0.1042
	Consistency ratio CR = 5.547087		Consistency index = 0.0916		

**Table 7** Priority and ranks of each Category

Sr. no	Category	Weight	Rank
1	Elevation	30.90%	1
3	Tsunami Direction	26.70%	2
2	Slope	23.90%	3
5	Coastal Shape	10.40%	4
4	Coastal Proximity	8.10%	5

using Shuttle Radar Topographic Mission (SRTM). For this purpose, using the bilinear interpolation, the 30-m grid was obtained from the 90-m grid through rationalizing. Elevations were ordered into five sets in view of the height of tsunami run-up at the coast and local regional knowledge (Table 1). The less elevated areas close to the coastline were given the high value of susceptibility, whereas the areas with high elevation were allotted lower value of vulnerability (Fig. 3). Thus, the high vulnerability zone encompasses mainly the seashore areas. This is because in these areas, the land is plain with less elevation.

### Topographic slope

For calculation of the topographic slope, Burrough and McDonnell (1998) algorithm is used. As tsunami has the potential of running onto plain and flat areas, exhibiting high speed and height, its waves can prove to be very destructive in different regions of a topographic gradient that is moderately smooth. In the current research, the slope has been sorted into five groups. The lesser slope indicates higher vulnerability and vice versa (Table 2). Areas along the coast or the seashore areas comprise of higher vulnerability zones since the land in this area is plain with a lower slope. This is indicated in Fig. 4.

### Tsunami direction

Another factor, which is of prime importance and must be adequately considered, is the direction of the tsunami. This is because the tsunami's direction has a great impact on its rapidity wave energy. It has been found that the regions, lying

**Table 8** Classification of tsunami susceptibility

Susceptibility Value	Class
< 1	Very low
1–2	Low
2–3	Medium
3–4	High
> 4	Very high

perpendicular to the direction of the flow of tsunami, exhibit a higher risk of being affected, owing to higher wave energy (Diposaptono and Budiman 2005). Conversely, the zones, lying tilted to the tsunamis' flow direction, are exposed to transition influences. Thus, it can be said that the intensity and severity of the catastrophe depend upon and are affected by each of these parameters. All of these parameters must be considered and given weightage, to gauge the severity and nature of the tsunami, as indicated in Table 3. Each of these factors is given weightage, depending upon the study area's geophysical characteristics, according to each grid cell, as given in Fig. 5.

### Coastal proximity

For the calculation of coastal proximity on a 30-m grid, a GIS layer map of the shoreline is used (Fig. 6). The impact of tsunami waves depends upon the distance from the shoreline. This means that with the increase in coastal proximity, the vulnerability increases. The following equation can be used to determine coastal proximity.

$$\log X_{\max} = \log 1400 + 4/3 \log (Y_o/10)$$

For the given equation,  $X_{\max}$  denotes the extreme impact of the tsunami across the land; beside this,  $Y_o$  denotes the tsunami height at the shore (Bretschneider and Wybro 1976). Regarding this formula, an area of approximately 100 m from the shoreline may be influenced by a tsunami having a height of about 5 m. For wave height of 5 to 10 m, the area of potential influence may rise to 100 to 200 m from the shoreline. Similarly, distances of 200 to 300 m and 300 to 400 m may be associated with wave heights of 10 to 15 and 15 to 20 m, respectively. Given these findings, coastal proximity has been grouped into five classes (Table 4).

### Coastal shape

Another factor that determines tsunami height and rapidity is the coastal shape. Thus, the lesser elevation of the coast may result in high run-ups compared with the coasts having higher elevation. This is because the wave dynamics change and directed towards gulfs. Figure 7 shows three zones of coastal shapes among which the study area was categorized into that include a cape, straight coast, and gulf. Each grid cell is given values (Table 5) depending upon the study area's geophysical features.

### Multi-criteria analysis

In this study, five geospatial variables were involved as conditions for tsunami susceptibility. These include coastal



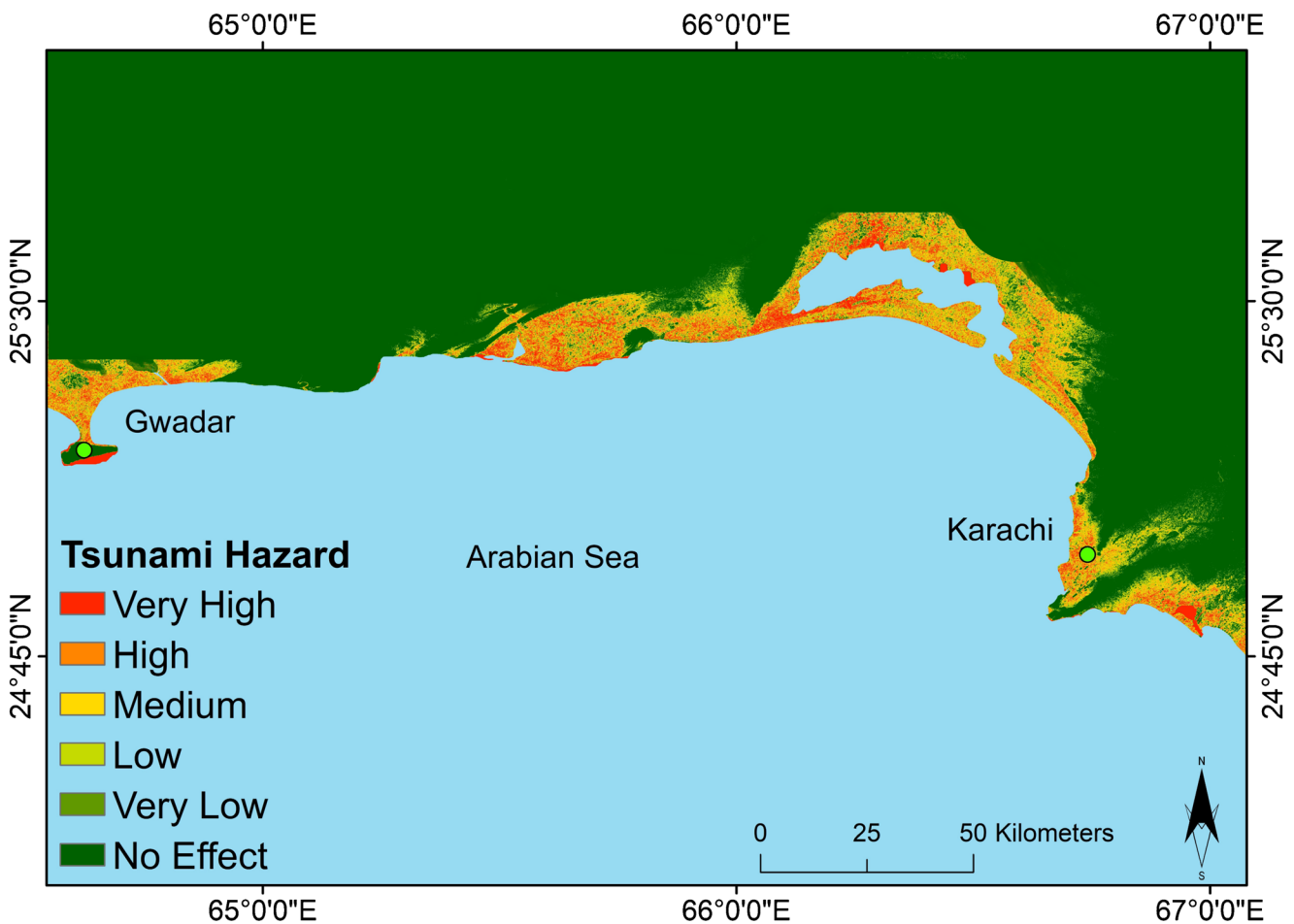


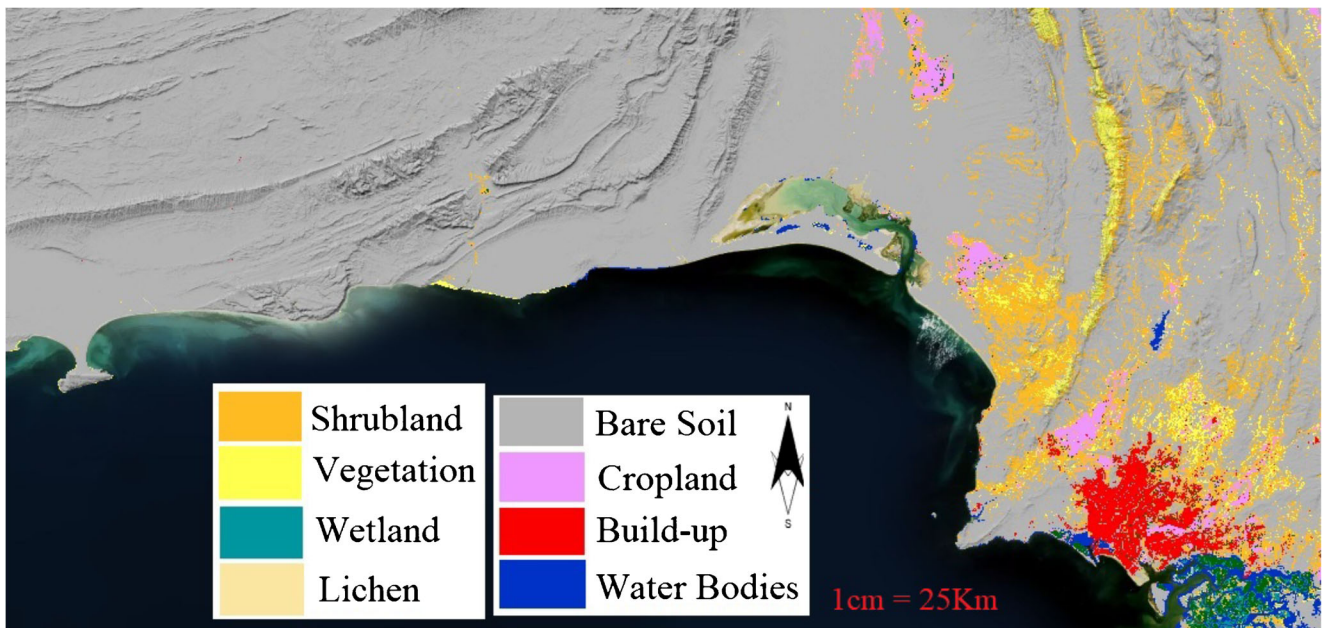
Fig. 8 Tsunami vulnerability map of Pakistan coast

proximity and shape, topographic elevation, topographic relation to tsunami direction, and topographic slope. For these variables, the weighted sum is calculated, and for each variable, its weight was calculated by the AHP technique. Priority adjustment for different parameters was obtained using AHP statistical study. This main has a significant influence on the intensity of the earthquake and the consequent tsunami hazard. In the AHP study, a decision problem is hierarchically simplified and easily understandable subproblems for an independent analysis. Different components of this hierarchy might concern to any feature of the original judgment question. After the creation of such a hierarchy, its various elements can be systematically evaluated by comparison (Herath and Prato 2006). Table 6 expresses the weights and the classification of each parameter resulted from AHP. To justify the weightages that these are not biased consistency value is calculated, if it is  $< 0.01$ , then it can be said as the calculations are not human biased which is justification of the results. It can be seen the Table 6 that this study has consistency value of 0.09 which means that the rating assigned to the

dataset is not biased. According to the tsunami run-up, the height of the ground is directly proportional to tsunami inundation. Therefore, maximum weight is given to the topographic elevation. Similarly, the association of the direction of the tsunami was given higher significance compared with coastal proximity. The reason for this significance lies in the fact that the resting land in the way at a right angle to the tsunami wave possesses higher vulnerability to be directly affected by the tsunami. Subsequently, low weights were assigned to coastal shape and coastal proximity as indicated by Table 7.

### Tsunami Mapping

Tsunami vulnerability has been developed by using the weight proportions calculated from the AHP process and combining them with the parameters through the weighted overlay method (Fig. 8). To utilize these parameters and to attain the susceptibility index for the area, equation  $\sum_{i=1}^5 w_i s_i$  is used as a weighted mean of parameters. Here, denotes the weightage of the  $i$ th dataset, whereas  $i$ th variable score is given by  $s_i$ .



**Fig. 9** Land cover map of the study area (Data source: Copernicus Global Land Service: Land Cover 100m, © Copernicus Service Information, 2019)

Each category was assigned different values, i.e., > 4 to “very high”, 3–4 to “high”, 2–3 for “medium,” and 1–2 for the “low” category, while < 1 is “very low.” The susceptibility values for about 1400,000 grid cells were within the range of 1.04 and 3.9. A standard deviation of 0.42 was found for the calculated mean of 1.5. In our study, there were four sorted classes for the values (Table 8). This was done by using Jenk’s natural break technique (Jenks 1963), which has the advantage of decreasing the sum of squared difference (SSD) within the group, to obtain homogeneity of the group. Regarding coastal area, the areas lying beside the shoreline and central cape as vulnerable and medium areas were observed to have a wide distribution of susceptible zones. This was probably due to its less elevation as well as the shape of the shoreline.

## Discussion

Within a GIS environment, this research explicated an examination of tsunami vulnerability at a regional scale by a multi-

criteria technique exercising geospatial variables. In producing a tsunami susceptibility map for coastal area of Pakistan, the analytical hierarchy process (AHP) was exercised to join five geospatial datasets which are coastal shape, elevation, coastal proximity, tsunami direction, and topographic slope. In case of incursion by the tsunami in the intended area a noteworthy section of buildup, the land is at risk as revealed by the association among the land use map and the tsunami susceptibility map. The coastal areas of Pakistan are characterized as vulnerable. They consist of a large number of people, and many important assets are located in these areas (Mahboob et al. 2015). Land use map was compared with the vulnerability map, to evaluate the danger for multiple types of land uses (Buchhorn et al. 2019). The land use map of coastal of Pakistan was prepared using the data from Copernicus Global Land Service: Land Cover 100m product (Fig. 9). This data is considered accurate considering its resolution, and this data further was classified into four classes because for tsunami, further division of crops or barren land is not required. The map consisted of four major classes of

**Table 9** Tsunami hazard with respect to land cover

Categories	Total area (km <sup>2</sup> )	Very high & high (% area)	Medium (% area)	Very low & low (% area)
Water	132.56	7	38	55
Vegetation	335.76	19	33	48
Buildup	276.54	16	35	49
Barren land	4235.67	23	34	43

land use which included water, buildup, and barren land besides vegetation. The buildup area largely consists of the land lying close to the coastline. The coastline areas are vulnerable areas for the majority proportion, with approximately 60% coastline areas falling under the vulnerability zones. The safe areas comprise the region lying far away from the sea. According to this study, considering the information mentioned above, over 30% of buildup areas are vulnerable to tsunami. Furthermore, the effects of this vulnerability extend over the clean water reserves of the city as well as coastal ecosystems such as marshes. Therefore, large-scale damage to life, property, and environment is likely to occur, in the event a tsunami striking the area at any point of time.

Table 9 shows the basic statistics of tsunami hazard potential to the different land use classes. It can be clearly seen from the Table 9 that about 16% of the buildup area of coast of Pakistan lies in very high to high zone of tsunami danger. This buildup area contains dense population of Karachi and Gwadar cities. Thirty-five percent of the buildup area falls in medium hazard and 49% have low hazard tsunami potential. Nineteen percent of the vegetation also falls in the danger zone along with 7% of the fresh surface water. While 50% of the area buildup, vegetation falls in low hazard zone because of the away from the sea line. Twenty-three percent of the barren land area is having high danger of tsunami, while 34% of the area has medium danger and 43% of the area has low threat form tsunami. The source of tsunami generation and its direction are the vital parameters to be estimated precisely because these factors can establish the association amid the approaching apex of a tsunami, its reach, and the extent of the destruction. For that particular reason, orientation and extent of divergent boundaries within the sea and major faults and their displacement details are important to cater to because these can define the estimated direction and height of the tsunami. According to the tsunami susceptibility map shown in this paper, major seaports like Bin Qasim port, Karachi port, Ormara port, and Gwadar port are situated in tsunami vulnerability areas. Further, the main residential and commercial infrastructure of Karachi city is also lying in the tsunami vulnerability zone which means that if a tsunami disaster occurs, it can cause a huge human and economic loss. Additionally, the study should be further extended to the microlevel, and data of streets roads, building heights, bridges, and commercial complexes should be obtained and taken into account for precisely mapping the extent of tsunami reach for the exact estimation of losses. As a sequel to this tsunami disaster study, GIS-based emergency evacuation plans should be formulated as an extended part of this study. Secondly, areas that are highly prone to tsunami strike in general, and particularly seaports and residential and commercial complexes should be precisely marked, and coastal embankments should be constructed at a constant interval of 50 m, and each embankment should have a height of 5 m with total tsunami blockage potential of 15 m height.

## Conclusion

The analysis based on GIS is of great importance as it is required in disaster evaluation, by using the spatial functionalities, i.e., topographic operations, the formation of a buffer zone, vicinity computation, map algebra, reclassification into raster format, and crossing operations. This type of strategy and approach can help us in regional planning for the administration department and can be a source to alleviate the consequences of environmental catastrophes like a tsunami. These analyses can, however, be constrained by the accessibility of data required to estimate the threat of environmental perils. To understand the disaster occurrences and damages, we must use more than five different geospatial variables in which encircle the suitable environment and socioeconomic data. A persisting potential risk is what preparation of a weighting scheme that ought to be a suitable one. The tsunami vulnerability maps can prove to be very productive in the efforts directed towards management and dealing with disasters in Karachi and Gwadar cities, keeping in view the tsunami catastrophes arising in the Arabian Sea.

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