Journal of Geography & Natural Disasters
ISSN: 2167-0587
Aslam et al., J Geogr Nat Disast 2017, 7:1
DOI: 10.4172/2167-0587.1000187
Research Article
Open Access

GIS Mapping of Tsunami Susceptibility: Case Study of the Karachi City in Sindh, Pakistan

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Abstract

The seaside region is a valuable zone that sustains many people and numerous bionetworks of biological and financial significance. Conversely, bionetworks and anthropological expenditures in seaside regions can be susceptible to regular catastrophes such as tsunamis. Around Pakistan, tectonic movement under the Indian Ocean has triggered numerous earthquakes and tsunamis. In this paper, we designate a GIS established multi-criteria examination of tsunami susceptibility for the city of Karachi in Sindh, Pakistan. We incorporate several geospatial variables of topographic elevation and slope, topographic relation to tsunami direction, coastal proximity, and coastal shape. We also incorporated proficient knowledge by the Analytic Hierarchy Process (AHP) to build a weighting order for the geospatial variables. In command to scrutinize tsunami susceptibility in relation to land use, we overlaid a land-use map on the tsunami susceptibility map. Buildings as well as residential and agricultural areas were found to be particularly at risk in Karachi. GIS based studies can assist in an extensive range of disaster valuation and expedite local forecasting for management and vindication of natural disasters such as tsunamis. We expect that the tsunami susceptibility map offered here will back the introductory tsunami vindication and management efforts in the Karachi seaside area.

Keywords: Anthropological; Tectonic movement; Earthquakes; Tsunamis; GIS; Analytic hierarchy process; Disaster

Introduction

Coastline areas make up merely 4% of the world's terrestrial area yet are home to one third of the world's inhabitants. According to the United Nations Environment Program (UNEP) World Conservation Monitoring Centre (2006), the coast line inhabitants may double in 15 years. In addition to human inhabitants, the seaside zone also provisions a diversity of ecosystems of high biological and financial significance, containing coral reefs, lagoons, sea-grass beds, sand dunes, mangrove forests, and other coastal vegetation. However, ecosystems and human expenditures in seaside regions can be susceptible to natural catastrophes such as tsunamis. Pakistan can suffer from earthquakes and tsunamis caused by seismic activity under the Indian Ocean. In contemporary 100 years between 1915 and 2015, around 100 substantial earthquakes have occurred in Pakistan. Maximum of tsunami incidents in Karachi have been initiated by tectonic earthquakes along Makran zone and along divergent boundary of Indo-Australian tectonic plate.

Using historical records, entire coastline of Pakistan has been an illustrious tsunami susceptible area. A wide range of seaside coastal city areas were estimated to be susceptible to tsunami dangers, including Makran, Gawadar, Badin and Karachi. An amount of studies have scrutinized the Indian Ocean tsunami, mainly which initiated near Sumatra. These studies included examinations of tsunami propagation models [1-4], impacts of the tsunami on natural environments [5], and ecological protection mechanisms against tsunami damage [6,7]. The 2004 Indian Ocean tsunami was one of the largest and deadliest tsunamis in recorded human history with 163,978 people dead.

Modern studies have examined tsunami susceptibility by evaluating various variables that can sway tsunami destruction. Such studies have collective variables into a susceptibility index using a weighted mean [8-13], but in most cases, the weighting order was somewhat subjective and not based on scientific foundation. As an alternative, Dall'Osso et al. [11] used the Analytic Hierarchy Process (AHP) as a more rational weighting technique. Nevertheless, their study concentrated on tsunami susceptibility at the small scale of individual buildings. In this paper, we entitle a GIS-based multi-criteria examination of tsunami susceptibility for Karachi, Pakistan. We used various geospatial variables such as topographic elevation and slope, topographic relation to tsunami direction, coastal proximity, and coastal shape. Whereas previous studies have analysed the physical features of buildings, we distributed with the regional environmental features to create a continuous map of tsunami susceptibility on a 30-m grid. Additionally, we exploited skilled awareness and employed the AHP technique to create a weighting scheme for the geospatial variables.

Study Area

Geographically Karachi lies at 24°51′ N 67°02′ E. Karachi is the prime metropolitan in Pakistan and capital of Pakistani province of Sindh. Karachi is the chief harbour and economic hub of Pakistan. Karachi metro has an likely inhabitants of over 23.5 million people as of 2013, and area of about 3,527 km^2(1,362 sq mi), ensuing in a density of more than 6,000 people per square kilometre. Its main land based on flat or rolling plains, with hills on the western side. The Arabian Sea outlines the southern shore of Karachi. Because Karachi is located on shore that's why it has a dry weather amid low average rainfall levels (approx. 9.8 in per annum), maximum of which occurs through the July–August monsoon season. Winters are warm and arid while the summers are scorching and sticky; the closeness to the sea maintains moisture levels at a near-constant high and cool sea breezes reduce the heat of the summer months. December to February is dry and pleasant as compared to the warm summers that dictate through the late spring (March) to the pre-monsoon season (June). Because of this

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Received September 29, 2016; **Accepted** January 27, 2017; **Published** January 31, 2017

Citation: Aslam B, Muhammad J, Muhammad ZI, Gulraiz A, Quaid IA (2017) GIS Mapping of Tsunami Susceptibility: Case Study of the Karachi City in Sindh, Pakistan. J Geogr Nat Disast 7: 187. doi: 10.4172/2167-0587.1000187

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city economic importance and large amount of population it is very important to study tsunami hazard of this city.

Seismicity of the area

Despite the fact that Southern Asia is seismically vigorous area, tsunamis all along the coastlines of Pakistan and India have been moderately uncommon, but not unique. Caustic earthquakes and tsunamis have occurred in the North Arabian Sea all the way through geologic history and in modern times. Most of these events have not been effectively recognized. On the western side of India, the earthquakes of 1524 and 1819 in the Kutch region perhaps generated destructive tsunamis. Many earthquakes occurred in the region in last 100 years which clearly indicates the active seismicity of the area (Figure 1). Damaging tsunamis are usually originated from large earthquakes along the subduction zone off the Makran coast of Pakistan in the past. Even though the historic record is deficient, it is supposed that such tsunamis were vicious on the coasts of Pakistan, Iran, India and Oman and perhaps had considerable effects on islands and other countries bordering the Indian Ocean. The mainly momentous tsunamigenic earthquake in fresh times was that of 28 November 1945. The tsunami was accountable for great loss of life and destruction along the coasts of Pakistan, Iran, India and Oman. The tsunami run-up heights mixed from 1 to 13 m.

The oldest known tsunami in the area may have been generated by a huge magnitude earthquake, which occurred in the Indus delta in 326 B.C. It has been cited in the literature [13], that this earthquake generated a tsunami in the Arabian Sea, which damaged Alexander the Great's Macedonian convoy on its voyage back to Greece after India's invasion. The Makran region has the prospective for very large earthquakes, which can cause destructive tsunamis in the prospect. Recent seismic activity indicates that a large earthquake is possible in the region west of the 1945 event [14]. Such an earthquake could generate a destructive tsunami. Karachi directly faces the Arabian Sea, the rifting site of the Eurasian, Australian tectonic plates. These plates are still stabilizing and have the possibility of sea floor spreading and seismicity. The Severe earthquakes have been reported around this area, and similar events could happen in the future. Since the above, approximation of tsunami susceptibility according to local environmental physiognomies can aid in the managing and exculpation of probable disasters.

Methods

Geospatial data processing

Topographic elevation: Topographic elevation is a prime circumstance to evaluate the tsunami susceptibility of a constituency. We calculated the Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) to attain the topographic elevations of the study zone. 30 m grid was obtained by rationalizing from 90 m grid using bilinear interpolation and elevations were categorized into five groups bearing in mind the tsunami run-up height at the coast and also the local knowledge of the area (Table 1). Near the coast less elevated areas are given the high vulnerability while higher the elevation lesser will be the vulnerability. Mostly seashore areas fall in the high vulnerable zone because the land has low and plain elevation (Figure 2).

Topographic slope: Topographic slope was calculated using the algorithm of Burrough and McDonnell [15]. Tsunami waves could be devastating in parts of moderately smooth topographic gradient as the tsunami can certainly run onto flat areas nevertheless might be incarcerated or repelled by hills adjoining the coastline. We employed the slope classification into five classes with lesser the area slope results higher vulnerable to tsunami and vice versa because less steep area means plain area where tsunami waves can easily run through (Table 2). Mostly seashore areas fall in the high vulnerable zone because the land is plain and low slope (Figure 3).

Topographic relation to tsunami direction: The direction of tsunami movement dissemination will affect its rapidity and elevation at the shoreline. Zones which are perpendicular to the track of a tsunami movement can be significantly affected by the extreme amount of energy of the wave [16]. Zones which are sheltered by other land features may be protected from the direction of a tsunami wave. Areas oblique to the direction of the tsunami wave may be subject to transitional effects. We allocated values to each of these three categories,

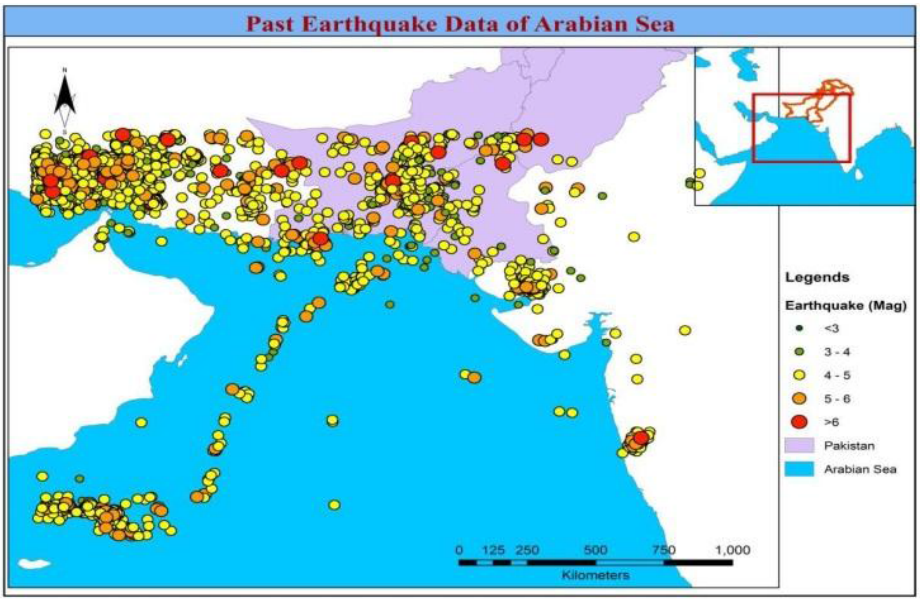

Figure 1: Earthquake record in the Arabian Sea and its surrounding.

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Elevation (m)	Susceptibility
4 or Lower	High
4 to 8	Rather High
8 to 12	Medium
12 to 16	Rather Low
16 or Higher	Low

Table 1: Susceptibility in terms of topographic elevation.

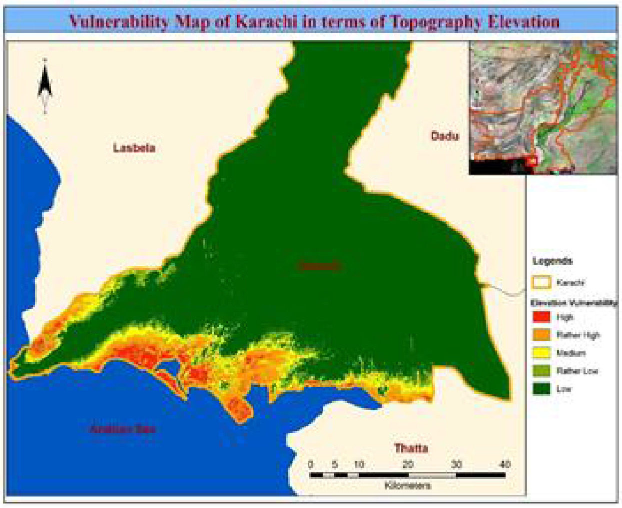

Figure 2: Susceptibility in terms of topographic elevation.

Topographic Slope (%)	Susceptibility
0 to 2	High
2 to 5	Rather High
5 to 9	Medium
9 to 15	Rather Low
15 or Higher	Low

Table 2: Vulnerability in terms of topographic slope.

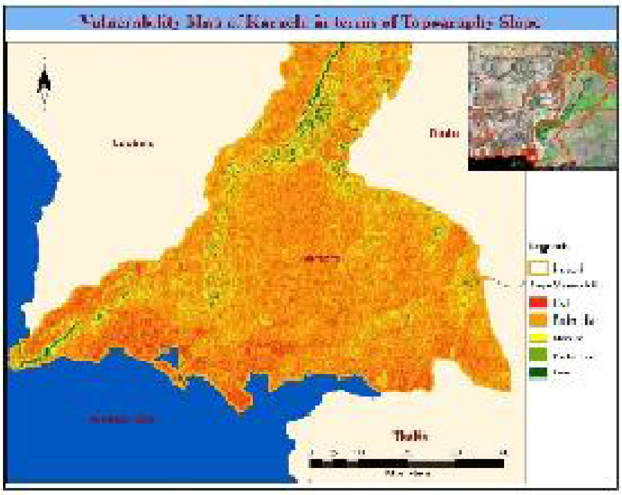

Figure 3: Vulnerability in terms of topographic slope.

as shown in Table 3. One of the values was then given to each grid cell according to the geophysical features of the study area (Figure 4).

Coastal proximity: By a vector map of the shoreline, coastal proximity has been calculated created on a 30-m grid (Figure 5). Distance from the shoreline is related with the potential influence of a tsunami wave. In general, susceptibility becomes higher as coastal proximity increases. To categorize coastal proximity, we

Topographic Relation to Tsunami Direction	Susceptibility
Perpendicular	High
Oblique	Medium
Covered	Low

Table 3: Vulnerability in terms of topographic relation to Tsunami direction.

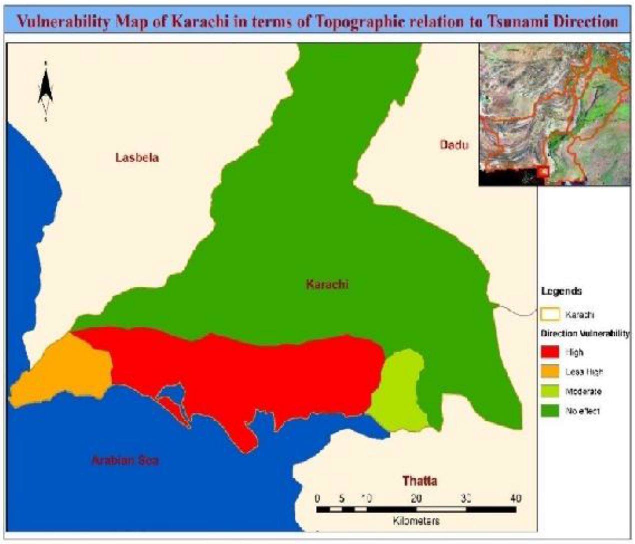

Figure 4: Vulnerability in terms of topographic relation to tsunami direction.

Distance (m) from Shoreline	Susceptibility
0 to 300	High
300 to 700	Rather High
700 to 1200	Medium
1200 to 1800	Rather Low
1800+	Low

Table 4: Vulnerability in terms of coastal proximity.

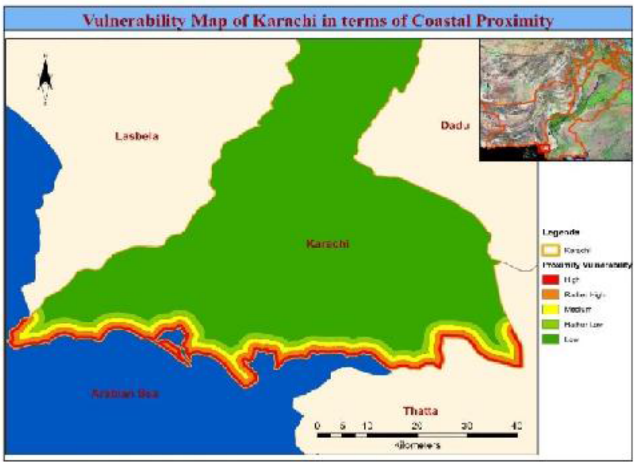

Figure 5: Vulnerability in terms of coastal proximity.

used the following equation from Bretschneider and Wybro [17]: $\log X_{max}=\log 1400+4/3\log (Y_o/10)$, where X_{max} is the maximum influence of the tsunami over land, and Y_o is the tsunami height at the shore. Conferring to this formula, a tsunami with a 5 m height can influence up to 556 m from the shoreline. 5 to 10 m wave height can reach up to 556-1400 m from the shoreline, whereas height of 10 m-15 m and 15 m-20 m correspond to distances of 1400 m-2404 m and 2404 m-3528 m respectively and so on. Based on these results coastal proximity categorized into five classes (Table 4).

Coastal shape: The shoreline shape is also stimulus tsunami height and rapidity. Coasts with depression may have higher run-ups than coasts without depression because wave dynamism lean towards to focus within gulfs. We divided the study area into three categories: gulf, straight coast, and cape (Figure 6), and allocated these categories to each grid cell by taking account of geophysical characteristics of the study area (Table 5).

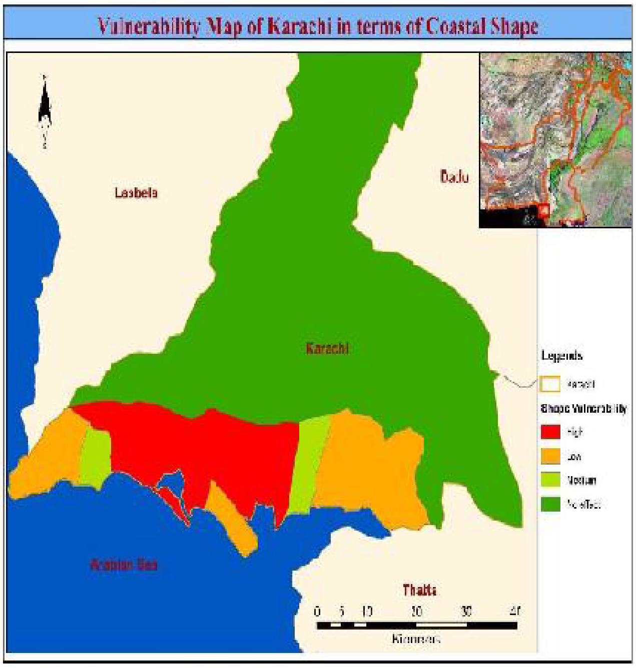

Figure 6: Vulnerability in terms of coastal shape.

Coastal Shape	Susceptibility
Gulf	High
Straight Coast	Medium
Cape	Low

Table 5: Vulnerability in terms of coastal shape.

Multi-criteria analysis and vulnerability mapping

Weighting scheme: Five geospatial variables used in this research, namely topographic elevation and slope, topographic relation to tsunami direction, coastal proximity, and coastal shape, as the conditions for tsunami susceptibility. Then the weighted sum of these variables has been calculated and the weight for all variables was calculated using the AHP tactic. AHP statistical study is used for the priorities adjustment of different parameters which may influence the earthquake intensity and hazard. In AHP, the decision problem is first decomposed into a hierarchy of more easily comprehended sub-problems that can be analysed independently. The elements of the hierarchy can relate to any aspect of the decision problem. Once the hierarchy is built, the decision makers systematically evaluate its various elements by comparing them to one another two at a time [18]. Table 6 shows the AHP study results of weights assign to each parameter and also the classification of each parameter [19]. Topographic elevation had the extreme weight since ground height is directly associated with tsunami inundation according to the run-up of tsunamis. The topographic relation to tsunami direction was considered to be more important than coastal proximity, because land lying perpendicular to the tsunami wave direction can be directly struck by the tsunami. Coastal shape and proximity had relatively low weights (Table 7).

Tsunami mapping

After combining all the parameters in weighted overlay with giving weight percentage according to AHP method, Tsunami vulnerability has been generated (Figure 7). To incorporate the parameters and obtain the susceptibility index for Karachi, weighted mean of the parameters is used in the form $\sum_{i=1}^{5} w_i s_i$, in it w_i is the weight of the ith variable, and s_i is the score for the ith variable. Values of 4, 3, 2, and 1 were assigned to the categories "Vulnerable," "Medium," "Rather Safe" and "Safe" respectively. The susceptibility values of around 1400,000 grid cells ranged between 1.04 and 3.9, with a mean of 1.56 and a standard deviation of 0.42. We classify values into four classes (Table 8) via Jenks' natural break technique, which decreases the within-group Sum of Squared Difference (SSD) to make inside homogenous group. In Karachi, vulnerable and medium areas were frequently found beside the shoreline and the central cape had a somewhat wide range of vulnerable areas, most likely because of its little elevation and shoreline shape.

Tsunami with the land-use

In the Karachi, a large amount of the inhabitants and important assets subsist within coastal areas classified as vulnerable. To scrutinize which types of land uses are in danger in further aspect, we compare the land uses with the vulnerability map. Land-use information in Karachi was obtained from the Research Article, "Remote Sensing and GIS Applications for Assessment of Urban Sprawl in Karachi,

Categories	Topographic Elevation	Topographic Slope	Topographic Relation to Tsunami Direction	Coastal Proximity	Coastal Shape
Topographic Elevation	1	3	0.5	3	3
Topographic Slope	0.333333	1	2	3	2
Topographic Relation to 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=0.121623	

Table 6: AHP table, comparison of factors and its weights.

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Factor. no	Category	Priority	Rank
1	Topographic Elevation	0.309	1
3	Topographic Relation to Tsunami Dir	0.267	2
2	Topographic Slope	0.239	3
5	Coastal Shape	0.104	4
4	Coastal Proximity	0.081	5

Table 7: Priority and ranks of each category.

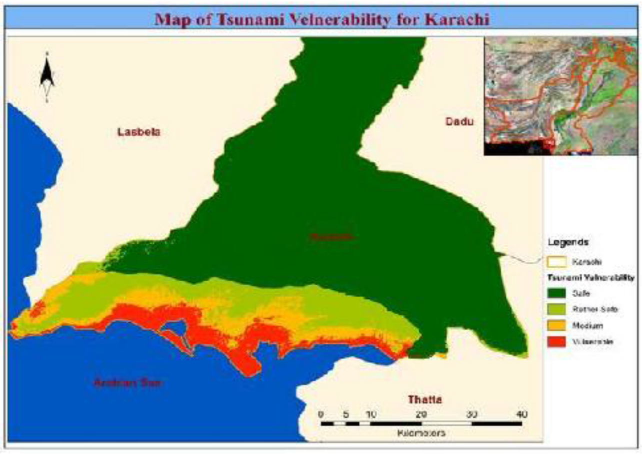

Figure 7: Tsunami vulnerability map of Karachi.

Vulnerability Value	Category
1.04 to 1.9	Safe
1.9 to 2.7	Rather Safe
2.7 to 3.4	Medium
3.4 to 3.9	Vulnerable

Table 8: Categorization of tsunami vulnerability.

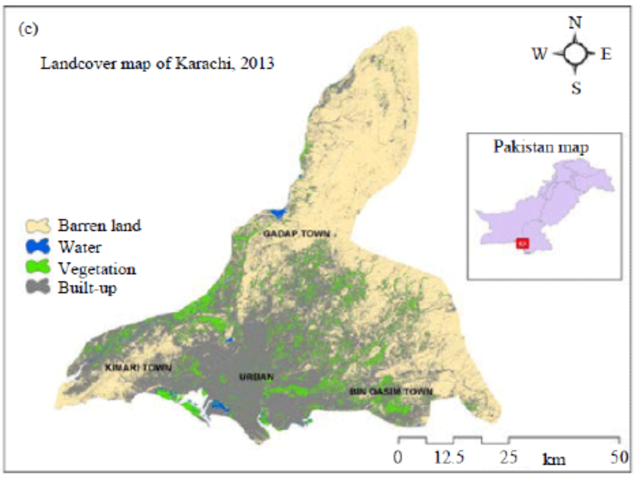

Figure 8: Land cover Map of Karachi [19].

Pakistan" (Figure 8). The map based on 4 major land-use classes counting Barren land, Water, Vegetation and Build-up. The majority buildings and housing areas are spread close to the coastline because of the flat topography and proximity to the sea. Vulnerable areas make up 90% of Karachi coastline, whereas safe areas cover entire region of Karachi which is far away from the sea. On the other hand, almost 70% of buildings and more than 30% of housing areas are in the vulnerable area, meaning that many people are at risk. In addition, clean water is also at danger, and coastal ecosystems such as marshes may be affected by a tsunami, even though their total area is comparatively small. As a result, tsunami occurrences around the Karachi have the probability to imperil human life, infrastructure, and the environment.

Discussion and Conclusion

In this paper, we have explained a multi-criteria investigation of tsunami susceptibility at a regional scale using geospatial variables within a GIS environment. We joint five geospatial variables (topographic elevation and slope, topographic relation to tsunami direction, coastal proximity, and coastal shape) using AHP and produced a tsunami susceptibility map for the Karachi, Pakistan. Comparing land-use with tsunami susceptibility map showed that buildings and residential area are at risk if a tsunami were to strike the study area. GIS-based analyses can be valuable in a wide range of disaster evaluation, through the use of spatial functionalities such as topographic operations, proximity calculation, buffer creation, raster reclassification, map algebra, and intersection operations. Such approach can assist in regional planning for administration and alleviation of natural disasters, including tsunamis. However, such analyses can be limited by the availability of data necessary for estimating the risk of natural hazards. We used just five geospatial variables. More adequate environmental and socioeconomic data will be required for better understanding of disaster occurrences and damages. Also, development of a more appropriate weighting scheme remains as a future work. Considering the tsunami catastrophes in Arabian Sea, we expect that tsunami vulnerability maps will contribute to beginning alleviation and development efforts in the Karachi.

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