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Research Article

GIS Based Tsunami Risk Assessment

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Abstract Tsunami is a coastal hazard which occur due to undersea earthquakes, Meteorite falls, volcanic eruptions or even nuclear weapon operations. The tsunami hazard which occurred in December 2004 was generated due to an undersea earthquake 400m west of northern Sumatra and it inundated coastal areas of Indonesia, Sri Lanka, Thailand and India. This hazard became one of the worst disasters in the history resulting in over thirty thousand fatalities and over seventy thousand house damage in Sri Lanka. This study is focused towards creation of GIS based Tsunami risk map for Galle city which was badly hit by the 2004 Tsunami. Tsunami vulnerability was assessed using weighted overlay spatial method with input parameters of population density, sex ratio, age ratio, disability ratio and damaged building ratio. Tsunami hazard map was developed based on tsunami inundation map which was published by Coastal research and design, costal conservation and resource management department with assistant from Disaster management centre using the Cornell Multigrid Coupled Tsunami Model (COMCOT). Vulnerable and hazard maps were analysed and incorporated to develop final risk map using GIS tool.

Keywords *GIS; Tsunami Inundation Map; Tsunami Risk Map; Vulnerability; Disaster*

1. Introduction

Tsunamis are series of giant waves generated as a result of earthquakes, landslides, volcanic eruptions or rarely meteorite impact under the sea (Kumar, 2008). Tsunami waves propagate with high speed and with a large wavelength in the deep sea. Due to its large wavelength, Tsunami waves travel large transoceanic distances with a minimum energy loss. When it approaches land and shallow waters, the amplitude of the wave rises up rapidly and it becomes a killer wave. Finally, it results in massive destruction in coastal areas (Wijesundara, 2014). 2004 tsunami disaster was the worst natural disaster ever faced by Sri Lanka. It completely disrupted socio-economic status of the country resulting massive life and property loss (Borah, 2007). It was a caution light to many countries in Indian Ocean to be prepared to face tsunami in future. Since Sri Lanka is located far away from any of the tectonic plate boundaries, its tsunami hazard probability is relatively low (Seismic Research Centre University of the West Indies, n.d.). Also, it takes considerable time for tsunami waves to reach Sri Lankan coast after an earthquake. Therefore, in a country like Sri Lanka, early warning and proper safety plans will lead to significant reduction in life losses and damages to property from same kind of disaster in the future. The severity of tsunami depends on the source, intensity of the causative factors and the distance from the epicentre (Ratna Sari, 2012). Since these factors are totally uncontrollable monitoring Tsunami hazards and preparing safety plans are the only options to minimize damages. Risk of the affected area depends on the vulnerability and the hazard. Demography, topography, land use pattern and construction type of the affected area determines the vulnerability and damage (Salap, 2018). Therefore, it is essential to identify the risk of the affected area in order to conduct disaster management activities. The main objective of this study is to develop a tsunami risk map for Galle city by analysing demographic data, past tsunami statistics, and tsunami inundation data with topographic data using GIS tools to facilitate disaster Management activities. Sri Lanka is well known for its natural attraction and fascinating historical sites. In addition to that it has a crucial geopolitical position due to its location as an island state in the Indian Ocean. The research is focused on Galle Four Gravets divisional secretariat which is the major urbanised commercial hub in Galle district, Sri Lanka. It consists with Galle harbour which is the only natural harbour that provides facilities to pleasure yachts in Sri Lanka. The city is nominated as a world heritage site by UNESCO due to its old city and fortifications, and is highly responsible for its tourist attraction. Eighteen Grama Niladhari divisions which were affected by 2004 tsunami were specifically selected as the study area. It is located in the Southwest coast of Sri Lanka at altitude 601’17” N -602’29” N and longitude 800 12’41” E to 800 14’ 56” E respectively (Wijetunge, 2006). (Figure 1)

Figure 1: *Tsunami affected GN divisions in Galle Four Gravets*

2. Methodology

Disaster risk is a function of two interrelated aspects of vulnerability and hazard (UNDP, 2004). In this study a boundary was defined as, tsunami vulnerability depends only on social and physical vulnerability and other contributing factors were not considered.

2.1. Material and Data

1) Demographic Data – Census data from Census & Statistics Department of Sri Lanka and Galle Four Gravets divisional secretariat office.
2) 2004 Tsunami statistics – Disaster management centre and Census & Statistics Department of Sri Lanka.
3) Social survey data – Questionnaire Survey.
4) Tsunami inundation map of Galle district based on the Cornell Multigrid Coupled Tsunami Model (COMCOT) from costal conservation and resource management department.

2.2. Tsunami hazard

The tsunami hazard map was developed analysing tsunami inundation map which was published by Coastal research and design, costal conservation and resource management department with assistant from Disaster management centre by using the Cornell Multigrid Coupled Tsunami Model (COMCOT). It is a computer model of waves generated by an event similar to the earthquake with magnitude 9.3 that occurred on 26th December 2004 in the Andaman-Sumatra subduction zone, which can be considered as the worst-case scenario faced by Sri Lanka. (Survey Department of Sri Lanka, 2012). Tsunami inundation shape file was created including three inundation depth ranges; less than 0.5, 0.5-2, greater than 2 meters. Further it was verified by field data.

Final hazard map was developed using weighted spatial method based on damaged levels obtained from the study done by Hettiarachchi et al. (2015) related to each inundation depth ranges. In that study constant high speed has been assumed for all inundation depth ranges. These weightage values given for different damaged levels can vary. Through further studies by considering socio-economic impact on damaged levels, more precise weightage values can be obtained, and they can be applied to this proposed framework to obtain more accurate results.

Table 1: *Weight analysis for hazard level*

	Life losses	Not permanent damage	Partially damaged	Totally damaged	Hazard level
d<0.5	-	1	-	-	0.16
0.5<d<2	3	-	2	-	0.83
d>2	3	-	-	3	1

2.3. Social Vulnerability

Social vulnerability stands for the potential damage or harm to people. It comprises of multiple factors that decide the degree to which one's life and livelihood are at risk in disaster or hazard occurring in nature or in the society. Social vulnerability differs from country to country also from area to area in the same country depending on demography of the particular area. When referring the literature so many methods that have considered various factors relevant to their data availability were identified. In this study the equation for social vulnerability was obtained from the study done by Farhan & Akhyar, 2017. Following equation was developed by changing some of the factors of that equation according to the data availability and the suitability of the location.

$$\text{Social Vulnerability} = 0.6 * (\text{Population index}) + 0.15 * (\text{Sex index}) + 0.15 * (\text{Age index}) + 0.1 * (\text{Disable index}) \quad (1)$$

2.4. Population Index

In a selected area with the increase of population its potential to harm increases. Population index is the main factor of this equation which has the highest contribution to the social vulnerability. Population density of each Grama Niladhari division of Galle Four Gravets were calculated according to the demographic data.

The population density range was categorized into several groups and weightage values were given to each group to calculate population index. The sensitivity and the accuracy of the results depend on the number of categorize groups. When the number of categorize groups increases sensitivity and the accuracy of the results also increased. In this study population density was categorized in to 30 groups and weightage values were given in the range of 1-30 to each GN division based on their population density. Then population index was calculated as a proportion of given weight of the GN division to maximum weight (30).

$$\text{Population index} = \frac{\text{weight of the GN division}}{(\text{Maximum weight (30)})} \quad (2)$$

2.5. Sex Index

From the biological and physiological built up females are less strong than males. According to the study of Neumayer & Plumper (2007) disaster response capacity of females are less compared to males. So when the female ratio increases the vulnerability increase. Since females are more vulnerable, sex index was selected according to the relevant female ratio.

2.6. Age Index

Elders and children are the most vulnerable groups in disaster events (Ngo, 2001; Cutter et al., 2003). According to the study of Martin et al (2006) Vulnerability of children are higher due to their lack of knowledge, life experiences, and essential resources to face the disaster successfully. Elders having physical, sensory or cognitive impairments are not competent enough to face disasters; therefore they are also more vulnerable (Rosenkoetter et al., 2007). In this study assumption was made that vulnerable age groups are age less than 18 and more than 60. Age index was selected according to the age ratio of vulnerable population by age to total population.

2.7. Disabled Index

People of any age having visual impairment, hearing and speech disorders, psychiatric disorders, physical disabilities, abnormal behaviours etc. are another vulnerable group. Disabled index was selected according to the disabled ratio of disabled population to total population of each GN division.

Table 2: *Parameters analysis for Age index, Sex index and Disable index*

Parameter	Percentage (%)	Variable	Index				
			0-20	20-40	40-60	60-80	80
Age index	15	Age ratio	0.2	0.4	0.6	0.8	1
Sex index	15	Female ratio	0.2	0.4	0.6	0.8	1
Disable index	10	Disable ratio	0.2	0.4	0.6	0.8	1

2.8. Physical Vulnerability

Physical vulnerability represents the possibility of physical damage to property in a disaster event. It depends on severity of the disaster as well as topography, land use pattern, type of the construction etc. In this study possibility of damage to buildings of a relevant GN division at present was assumed as similar to that of 2004 situation, because topography (hill area, flat area), land use patterns are not changed. So, even though the number of buildings increased property damage ratio is same. Therefore, in this study physical vulnerability of each GN division was calculated as a ratio of number of damage house units and non-house units to total number of existed buildings before the tsunami disaster. 2004 tsunami statistic data from department of Census and statistics was used for these calculations.

$$Physical\ Vulnerability = \frac{No\ of\ damged\ house\ units\ and\ Non\ house\ units}{\text{Total Number of buildings before the 2004 tsunami}} \qquad (3)$$

2.9. Tsunami Vulnerability

Since Sri Lanka is located far away from any of the tectonic plate boundaries, its tsunami hazard probability is relatively low. Also time taken by waves to reach coastal area is high. Therefore, in a country like Sri Lanka, there is higher survival possibility if people are aware about hazard and safety precautions. Tsunami Vulnerability is obtained from analysis of equation 4. Components of equation represent the effect of social and physical vulnerabilities to tsunami vulnerabilities respectively. Effect of the social vulnerability was derived based on awareness of the people about tsunami disaster, early warning system, safety actions that should be taken prior to a tsunami, which were analysed via the questionnaire survey. It was conducted among three age groups; age <18, 18<age<60, 60<age. People below 18 were identified as unaware group as shown in Figure 2. Therefore, the effect of social vulnerability was derived as a ratio of unaware population to total population. According to the assumption that tsunami vulnerability depends only on social and physical vulnerabilities therefore sum of the components should be equal to one. Hence value of the second component is derived depending on the value of the first component.

$$\text{Tsunami Vulnerability} = 0.35 * (\text{Social Vulnerability}) + 0.65 * (\text{Physical Vulnerability}) \qquad (4)$$

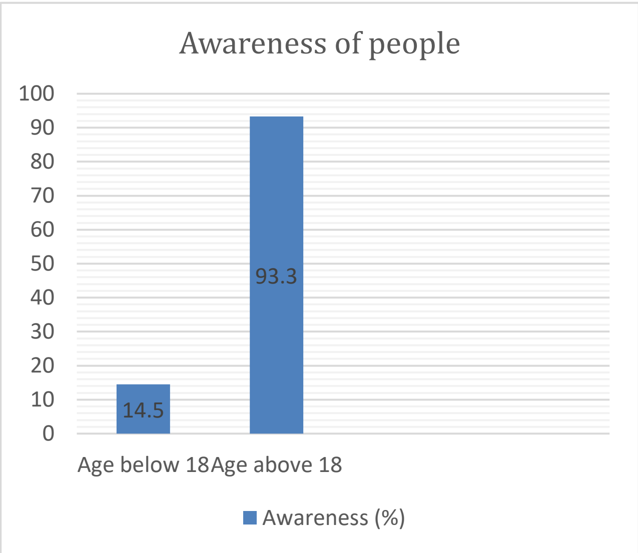

Figure 2: *Summary of questionnaire on people's awareness of the tsunami*

2.10. Tsunami risk

Tsunami risk is a function of two interrelated aspects of vulnerability and hazard. Thus it was analysed from weighted overlay spatial method based on tsunami vulnerability and hazard. This equation was considered according to the study of Farhan & Akhyar, (2017).

$$Risk = \sqrt[2]{Hazard * Vulnerability} \qquad (5)$$

3. Result and Discussion

Level of damage related to each inundation depth range is one of the most important parameter for developing tsunami hazard map. Damage levels can fluctuate in the same inundation depth for different wave speeds. Damaged levels were analysed assuming constant wave speed according to a previous research. Figure 3 indicates the tsunami hazard map for Galle Four Gravest which was developed integrating hazard levels for each inundation depth ranges using Arc GIS tool. Tsunami hazard raster was classified into 3 stages as low, moderate and high. The social vulnerability map is derived by combining effect of population index, sex index, age index and disabled index parameters in a GIS environment. These 4 indexes were combined according to the equation (1). The most effective parameter was identified as population index with a weight of 0.6, which is the most contributed parameter compared to others. Hence areas that are extremely overcrowded often exhibit higher social vulnerability. Figure 4 indicates the social vulnerability map for Galle Four Gravets which represents 3 different vulnerability stages as low, moderate and high. Physical vulnerability is given in Figure 5. Physical vulnerability at a specific location depends on the land use pattern and topography. According to the map highly affected areas can be recognized with higher building damage ratio. Flat terrain and higher building density have led to vast destruction. Physical vulnerability raster was classified into 3 vulnerability stages as low, moderate and high. Tsunami vulnerability map is derived by integrating social and physical vulnerabilities respect to equation (4). 0.35 and 0.65 components represent effect of social and physical vulnerabilities to tsunami vulnerability respectively. Due to high contribution of physical vulnerability, tsunami vulnerability map (Figure 6) and physical vulnerability map show approximately similar colour tone. The most tsunami vulnerable Dewathura area shows dark red colour and minimum tsunami vulnerable Minuwangoda area shows dark green colour. The value of social vulnerability, physical vulnerability and tsunami vulnerability maps are in the range of 0-1.

Table 3: *The computed vulnerability values for affected area*

GN no	GN Division	Social vulnerability (SV)	Physical vulnerability (PV)	Tsunami vulnerability 0.35*(SV) + 0.65*(PV)
96G	Cheena Koratuwa	0.28	0.591	0.482
102A	Dadalla East	0.5	0.099	0.239
102	Dadalla West	0.32	0.445	0.401
100A	Dewata	0.28	0.623	0.503
99D	Dewathura	0.35	0.720	0.590
103A	Ginthota East	0.32	0.144	0.206
103	Ginthota west	0.23	0.346	0.306
96C	Kaluwella	0.27	0.537	0.443
100	Katugoda	0.41	0.581	0.521
99	Magalla	0.3	0.501	0.431

96A	Mahamodara	0.29	0.596	0.489
96H	Minuwangoda	0.34	0.093	0.180
99B	Pettigalwatta	0.28	0.535	0.445
102C	Siyambalagahawatta	0.27	0.222	0.239
99A	Thalapitiya	0.77	0.449	0.561
102B	Walawwatta	0.32	0.189	0.235
105	Welipitimodara	0.25	0.214	0.226
97A	Weliwatta	0.31	0.579	0.485

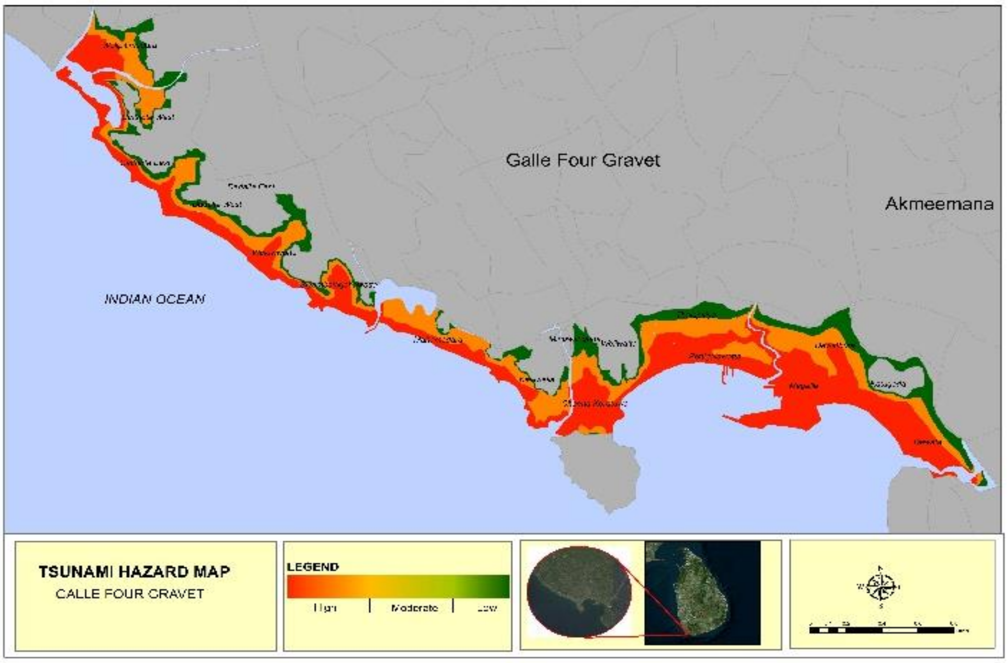

***Figure 1**: Tsunami hazard map*

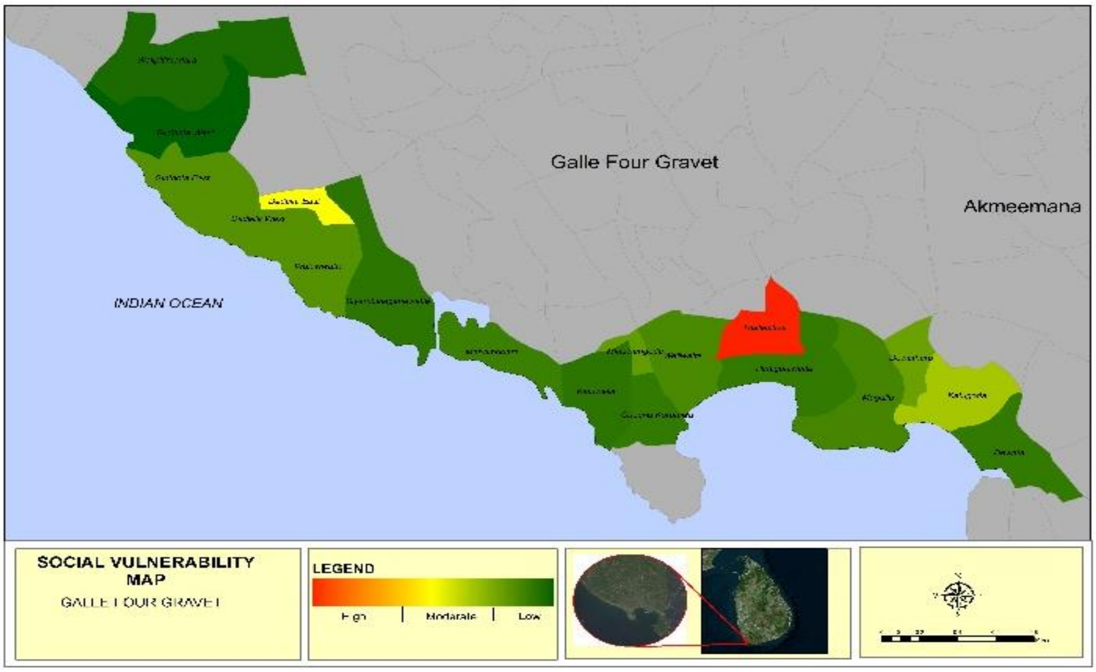

***Figure 4:** Social vulnerability map*

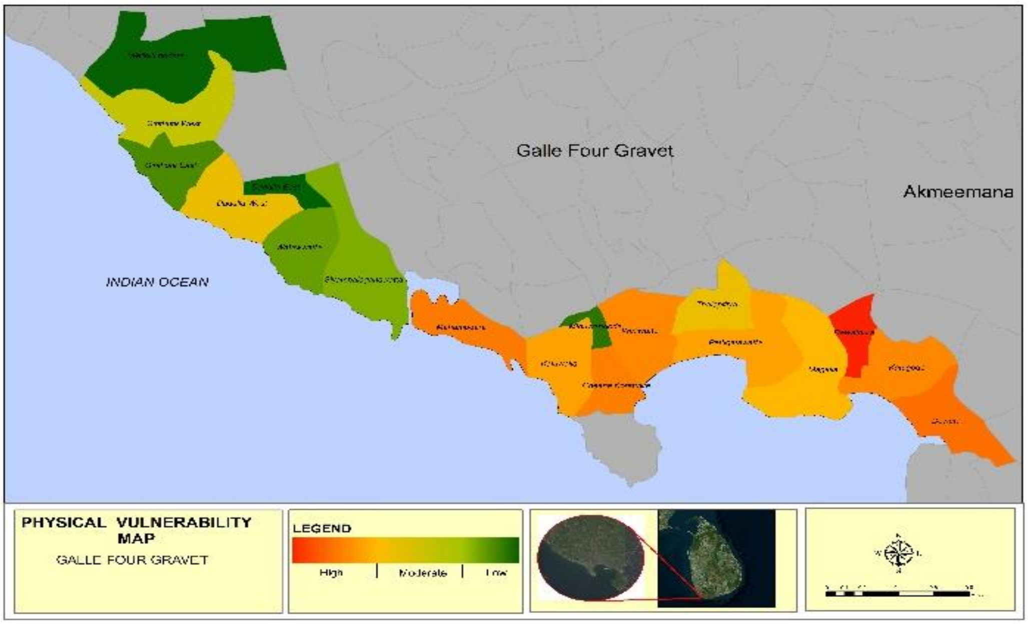

Figure 5: *Physical Vulnerability map*

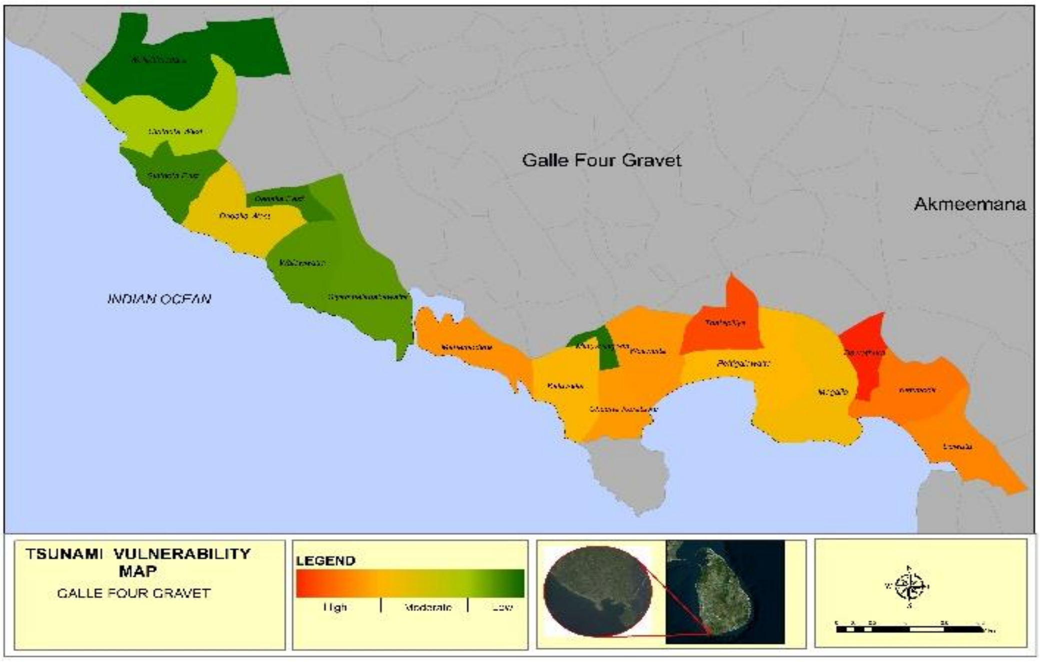

Figure 6: *Tsunami Vulnerability map*

Tsunami risk map is based on hazard and vulnerability. Risk of each area was obtained from analysing equation 5. The value of the tsunami risk in the range of 0-1. It fluctuates with inundation depth ranges in same GN divisions. Hence, Colour tone gradually vary in same GN division with the distance from the shoreline. The area with grey colour represents the zero value as it is not inundated by tsunami waves. According to the colours in the map Galle port, International cricket ground, Bus terminal and Train station are at high risk zone. But the ancient Galle fort is safe from the tsunami waves due to its huge stone walls. According to the map though maximum hazard level (from depth>2m) shows some areas in west coast region shoreline of the affected area shows maximum hazard level but the risk is moderate due to low tsunami vulnerability.

Table 4: *The computed risk values for affected area*

GN no	GN Division	Tsunami risk		
		Depth<0.5	0.5< Depth < 2	Depth>2
96G	Cheena Koratuwa	0.278	0.632	0.694
102A	Dadalla East	0.196	0.446	0.489
102	Dadalla West	0.253	0.577	0.634
100A	Dewata	0.284	0.646	0.709
99D	Dewathura	0.307	0.700	0.768
103A	Ginthota East	0.181	0.413	0.453
103	Ginthota west	0.221	0.504	0.553
96C	Kaluwella	0.266	0.607	0.666
100	Katugoda	0.289	0.658	0.722
99	Magalla	0.262	0.598	0.656
96A	Mahamodara	0.280	0.637	0.699
96H	Minuwangoda	0.170	0.386	0
99B	Pettigalwatta	0.267	0.608	0.667
102C	Siyambalagahawatta	0.195	0.445	0.489
99A	Thalapitiya	0.300	0.682	0.749
102B	Walawwatta	0.194	0.442	0.485
105	Welipitimodara	0.190	0.433	0.476
97A	Weliwatta	0.279	0.634	0.696

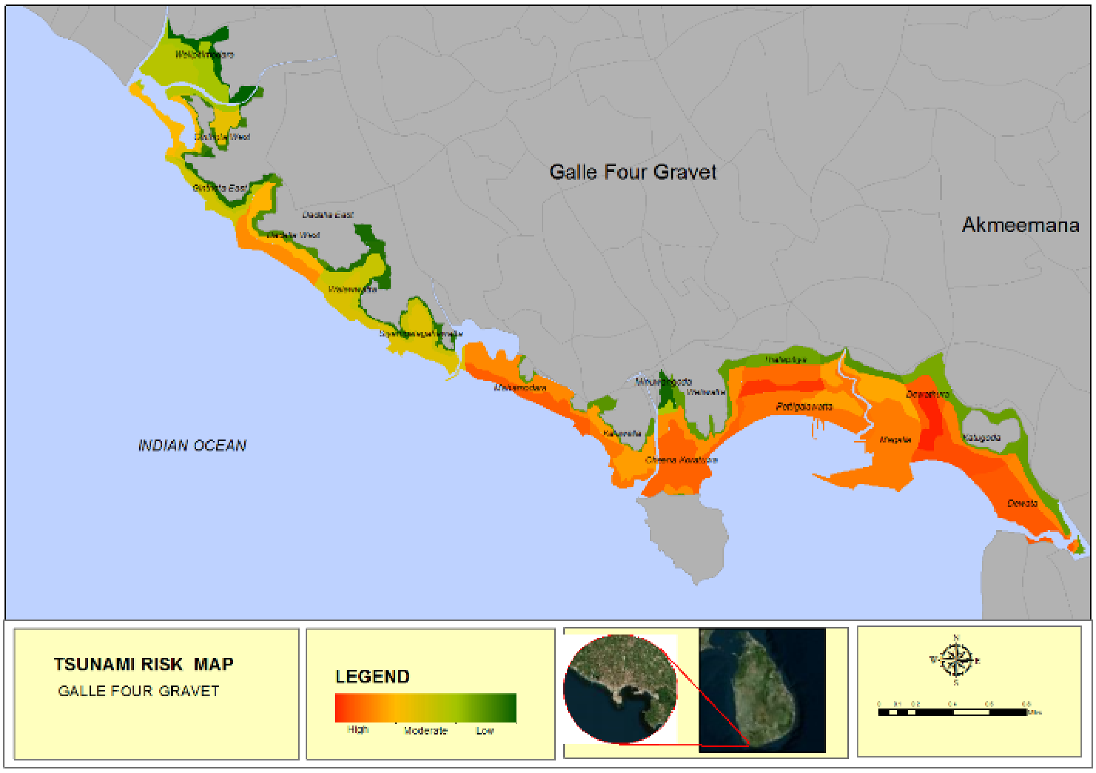

Figure 7: *Tsunami risk map*

4. Conclusion

Tsunami Risk is a combination of hazard and vulnerability (Figure 7). In this study, the tsunami hazard map was developed analysing tsunami inundation map which was published by disaster management centre by using the Cornell Multigrid Coupled Tsunami Model (COMCOT) and damage levels were taken from past research data. The validation of the final output with field surveyed data on the 2004 tsunami event shows an 80 % match with the field observations. Highest tsunami risk shown at Dewathura while Dewata, Thalapitiya, Mahamodara, Katugoda, Pettigalawatta, Dadalla west, Kamuela, Weliwatta have included with high tsunami risk zones. According to the risk map 58.44 % of the study area belongs to high risk zone while 20.46 % belongs to moderate and the rest 21.10 % belongs to low risk zone.

In this study, a boundary was defined that tsunami vulnerability depends only on social and physical vulnerability. Questionnaire survey and reconnaissance survey were conducted to analyse the awareness level of the people about tsunami disaster, early warning system and safety precautions in order to find contribution of social and physical vulnerability for total vulnerability. According to that people in the age group below 18, has 14.5% of very poor awareness level about tsunami, warning system and safety actions that should be taken prior to a tsunami while people in the age above 18 has 93.3% of better awareness. Previous exposure and experiences in tsunami disaster should have resulted this deviation. Further lack of awareness programmes and education on tsunami disaster at present has also contributed for that. If this continues further, the awareness of the community will gradually deteriorate, and it may result in similar damage in the future.

Social Vulnerability depends on several factors including population density which contributes mainly. Highest social vulnerability shows at Thalapitiya which has highest population density compared to others. Highest tsunami risk and physical vulnerability shows at Dewathura which represented highest building damage rate in 2004 tsunami disaster due to its low elevation, topography and land use pattern.

This study provide depicts variations in tsunami risk along the Galle coastal belt. Outcomes of this study are useful for decision makers in deciding early warning, planning evacuation activities and township development. So that this will ultimately minimize damages in future disaster.

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