Earthquake Hazard Micro Zonation in Fiji Islands: A Research of VitiLevu Island

Joeli Varo, Tingneyuc Sekac, Sujoy Kumar Jana

Abstract: Depending on magnitude the earthquake hazards can have collateral retort of devastations in collusion with the site-soil geology. Fiji – Tonga region accounts for about 70 percent of the world's earthquakes with depths greater than 400 kilometres. Risk management through spatial planning is paramount for tectonism linked disasters in order to reduce the extent of fatality and economic cost. Humanity is at the 'tipping point' of self-destruction unless knowledge on disaster risk reduction is disseminated on time in the form of implementable solutions such as using ArcGIS as a tool to provide worthwhile segmentation of disaster prone zones to administrators. The present study aims at assessing the site-soil geology and earthquake hazard potentiality of VitiLevu Island using the GIS and remote sensing techniques. Site-soil geology, geomorphology, seismology and SRTM DEM data were the main sources of layers used to carry out analysis using the Saaty's Analytical Hierarchical Process (AHP) and ArcGIS Multi-Criteria Analysis (MCA).The technology involves preparing and assessing several contributing factors (thematic layers) those are assigned with weightage and rankings, and finally normalizing the assigned weights and ranking. In the ArcGIS 10.5 spatial analyst tool, the raster calculator, reclassify and weightage overlay tools were mainly employed in the study. The final output of EHZ indicates the 'low', 'moderate' and 'high' zones of potential earthquake disasters. The result provides a substantial readable guide for urban and regional spatial planners as well policy makers to formulate disaster reduction policies. Thus, informing civil societies, private societies and community to become well - versed with adaptive strategies suitable to withstand and encounter earthquake hazards.

Keywords: Multi – Criteria Analysis. GIS.Liquefaction Potential Zones.Earthquake Hazard Zones.Disaster Risk Management.

I. INTRODUCTION

According to Miles et al. (1999), researchers and practitioners in earthquake engineering have recognized geographic information system (GIS) to be a significant and vital tool in modelling spatial phenomenon related to hazard and risk. GIS, as an engineering tool has been primarily used for its spatial data storing and presentation features.

This present study endeavoured into identifying potential areas of earthquake hazards in VitiLevu Island. In lieu, lithology structure, seismicity layers such as fault lines, fracture zones, lineaments and soil attributes were integrated with ease using the GIS to achieve the desirable output. There were numerous similar approaches undertaken around the world on this specific discipline which highlights the essential role of GIS in Disaster Risk Reduction (DRR) and Disaster Risk Management (DRM).

The paramount aim of this research is to demarcate earthquake hazard zones on VitiLevu Island. Hence, the following three (3) objectives were thoroughly considered in order to fulfil this aim; (1) Identify bio-environmental factors that cause liquefaction, (2) Analyse and synthesize the collected data through Analytical Hierarchical Process (AHP), Multi – Criteria Analysis (MCA) and advanced GIS environment, and (3) Demarcate the earthquake hazard zones and highlight the socio-economic, physical and environmental measures to reduce earthquake hazards risks. Hence, the aim is to provide substantiative evidence for sound and well-informed decision making.

GIS based approach is widely used to identify earthquake related hazards such as earthquake hazard zonation, liquefaction, landslide, flood, fire and tsunami. According to Fernández et al. (2010),the five parameters incorporated to produce an urban flood hazard zoning in Tucumán Province, Argentina were: distance to the drainage channels (D), topography (heights and slopes) (H & S), ground water table depths (GWD), and urban land use (LU).

Pal et al. (2007) stated that the earthquake hazard zonation of the Sikkim Himalaya was prepared from analysing and assessing 8 thematic layers within the GIS based-decision support system. Those 8 thematic layers namely; slope (SL) soil site class (SO), geology (GE), rock outcrop (RO), land slide (LS), simulated peak ground acceleration (PGA), frequency wave number (F-W), site response (SR) and predominant frequency (PF) were used in geographic information system (GIS) platform. Weightage and ranking were assigned to individual thematic layer according to literature, expert opinion, discussion and past best practices. Then, the normalized weight and rank were retrieved using Analytical Hierarchical Process (AHP). Finally, the output was the seismic and geohazards zones of the Sikkim Himalaya.

In another study, Sekac et al. (2016) revealed that the demarcation of liquefaction susceptible zones was prepared from analysing 6 thematic layers with GIS platform. Those 6 thematic layers namely; fault buffer (FB), geology (GE), slope (SL), soil drainage (SD), soil texture (ST) and soil average water holding capacity (SAWC) were utilised in the state of the art geographic information system (GIS). Weightage and ranking were assigned to individual thematic

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layer according to literature, expert opinion, discussion and past best practices. Then, the normalized weight and rank were retrieved using Analytical Hierarchical Process (AHP). Finally, the output was the liquefaction potential zones of Madang and Morobe province in Papua New Guinea.

II. STUDY AREA AND RESEARCH METHODOLOGY

The World Bank (2015), revealed that the expected annual losses for Fiji Islands over the long-term period is F$158 million (US$84 million) caused by tropical cyclones and earthquakes. Fiji Islands is located at 1780 East and 170 South on global coordinate system, have a total of 322 islands, atolls and islets with about 50% of those are yet to be inhabitable by human beings. The Fiji Bureau of Statistics (2017) revealed that 76.6 % or 678,153 out of 884,887 of Fiji's total population lives within the case study area alone called VitiLevu Island. According to Rahiman and Pettinga (2008), VitiLevu, the main island of Fiji has a total land mass of approximately 10,344 Square Kilometre (Figure 1), is located in a seismically active area within the Fiji Platform, a remnant island arc that lies in a diffuse plate boundary zone between the Pacific and Australian tectonic plates in the South West Pacific. VitiLevu is the largest in the Fiji Islands and is the site of the capital city, Suva. It comprises two cities and 10 towns. According to Burke et al. (2011) and Lata et al. (2012) all these urban centres are coastally located within 30-meters from mean sea level and are highly vulnerable to flood, tsunami and earthquake.

Gupta (2003), Theilen (2009) and Sekac et al. (2016) revealed that local site conditions play an important role in determining the earthquake destruction locally, it depends on the built infrastructures, proximity to fault lines and fractures, bedrock structures, subsurface ground conditions and the unconsolidated substrate saturated with water.

Suva city is considered to be an extremely high vulnerable zone to earthquake and tsunami. Indeed, Houtz (1962) and Rynn et al. (2000) attested to this, with the memory of the devastating 14thSeptember 1953 Suva earthquake (Richter Magnitude ML 6.5) which killed 2 people and its devastated landslides, tsunami and destruction of physical infrastructure estimated worth of US$900,000. This earthquake had an epicentre at 18020' South, 178030' East (off the Navua-Naqara coast of Southeast VitiLevu) approximately 15-20-kilometre (km) southeast of Suva city.

Rodda (1967) and Parson et al. (1990) revealed that Fiji Islands represent a portion of the old Vityaz Arc which was split up and rotated clockwise to its present position. The breakup of the Vityaz Arc probably reflected in the strong faulting and folding of 12 to 17—million-year-old rocks in southwest VitiLevu. This was also a period of great volcanic activity in Fiji and the whole region. Fiji is located at the Indo– Australian and the Pacific plate boundary between two opposites– facing subduction zones and hence has a very complex tectonic history. The stresses created by the opposing plate movements have resulted in the formation of transform faults such as the Fiji Fracture Zone to the north and the Hunter Fracture Zone to the south. Seafloor spreading resulted in divergence and opening up of the North Fiji Basin and the Lau Basin (Fiji Mineral Resources Department, 2015) and (Rahiman and Pettinga, 2008).

Researchers such as Sykes et al. (1969), McCue (1999),Stirling et al. (2014) and Everingham (1986) revealed that Fiji – Tonga region accounts for about 70 percent of the world's earthquakes with depths greater than 400 kilometres. This region seemed to be the natural choice for intensive study of various aspects of deep earthquakes and of the relationships of these earthquakes to tectonic processes in island arcs. Thus, the Fiji- Tonga region is an important testing ground for various theories of global tectonics such as the hypotheses of mantle convection currents, continental drift, sea-floor spreading, and movements of large plates of lithosphere.

In addition, scientists and researchers such as Bartholomew (1959), Shackleton (1936) and Hirst (1965) geological studies revealed that Fiji is largely built of coalescing volcanic structures and its geology is dominated by volcanic and volcanoclastic rocks together with associated intrusive and sedimentary rocks in local basins. Figure 1 indicates the location of study area.

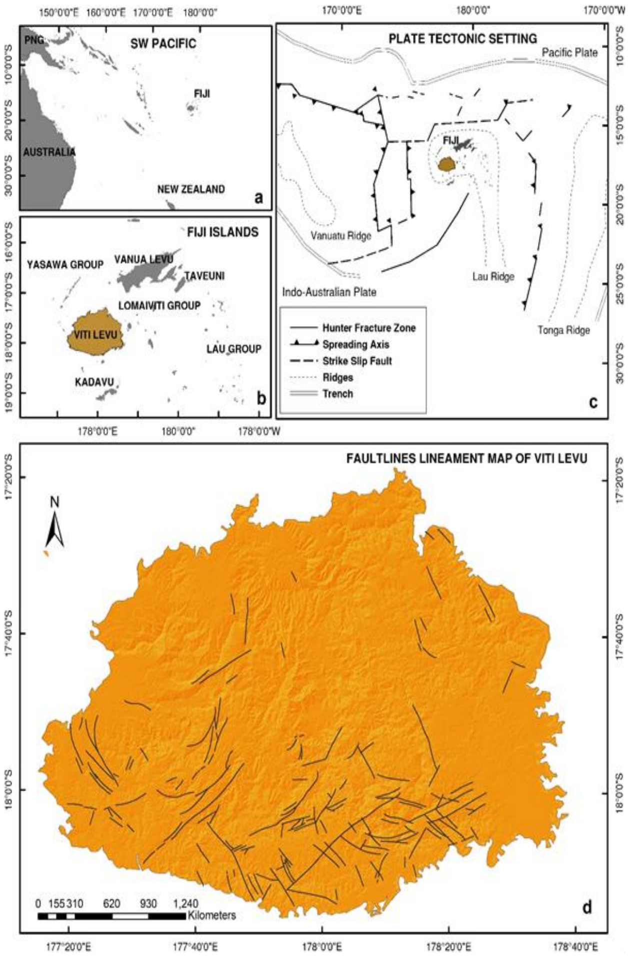

Figure 1. Locality maps; a Location of Fiji in the Southwest Pacific and, b the main islands of the Fiji archipelagos, c plate tectonic settings, d VitiLevu fault lines & lineaments which is case study area

2.1 Data collection and pre-processing

The six (6) thematic layers that were used to demarcate liquefaction potential zones were retrieved accordingly. For geological map (GE) comprising lithology and structure of Fiji Islands was retrieved from Fiji Mineral Resources Department. It was georeferenced using ERDAS IMAGINE 8.5 in (.img) format where the boundary was digitized, and then it was translated to shapefile (.shp) format for further digitization and analysis. In ArcGIS 10.5, the lithology shape file was digitized into three (3) classes which were consolidated, semi-consolidated and unconsolidated. These three (3) classes were based on expert opinion, literature, experiences, discussion and available research carried out on Fiji's geology. Thus, after digitization of these three classes, the shapefile (.shp) were translated to raster (.img) format in order to prepare for raster calculator analysis in GIS.

Soil map was retrieved from Fiji Mineral Resources Department and cross checked with Fiji Ministry of Agriculture Land Use Guideline. The three (3) attributes of soils used in this present study were soil texture, soil drainage and soil average water holding capacity. Weightage and ranking were assigned based on expert opinion, literature, experiences, discussion and available research carried out regarding Fiji's soil attributes. The soil map was georeferenced in ERDAS IMAGINE and saved as tab file (.tab) format, then translated or converted to shapefile (.shp) format for further analysis in ArcGIS. All these soil attributes were individually converted to raster (.img) format in order to perform further analyses using raster calculator in ArcGIS.

Furthermore, seismotectonic data provides fault lines, deep strike and folding occurrence on VitiLevu Islands only was provided by the Secretariat of Pacific Islands Community (SOPAC) in reference to Fiji Minerals Resources Department. These layers were in (.tab) format and converted to shape file (.shp) format for further spatial analysis. Slope layer was derived from the 20-meter contour layer (.shp) and converted to slope using the ArcGIS conversion toolbox. Now, all these six (6) layers were in (.shp) format being converted to raster using the ArcGIS feature to raster tool in the tool box. Finally, all the six layers were ready to be assigned with weights and rating according to the probability of liquefaction using the Saaty's Analytical Hierarchical Process (AHP).

Fiji seismicity data are recorded and updated as it happens or on a real time basis by the United States Geological Survey Earthquake catalogue after every earthquake event. For this present study, all necessary earthquake data such as date of earthquakes, earthquake depths and magnitudes were retrieved and downloaded in an excel (.csv) format within 2000 to 2017 time period. The total number of earthquakes recorded within this 17 years time period for the study area and the surrounding were 4033. Figure 2 below represents the earthquake distribution in depths for Fiji Islands as a whole while Figure 3 illustrates the earthquake distribution in magnitudes for the study area. Figure 4 and 5 on chart and graph below revealed all necessary detailed information of earthquakes distribution in Fiji Islands.

For earthquake data, it was observed that earthquakes depths exceed 700 kilometres along this Fiji – Tonga boundary and became sparsely distributed when moving towards VitiLevu Island. Moreover, Figure 5 below revealed astonishing information when thoroughly contemplated, that is 2017 recorded 58 earthquake events within this 17-year period. Hence, earthquake continues to increase its intensity, magnitude and frequency from time to time.

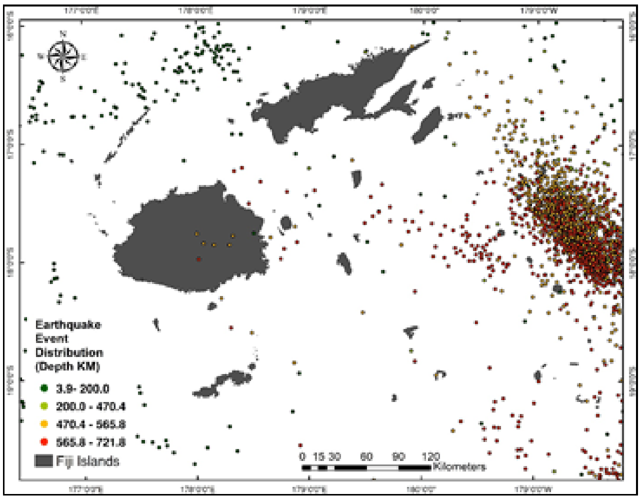

Figure 2. Earthquake event distribution in depths for Fiji Islands

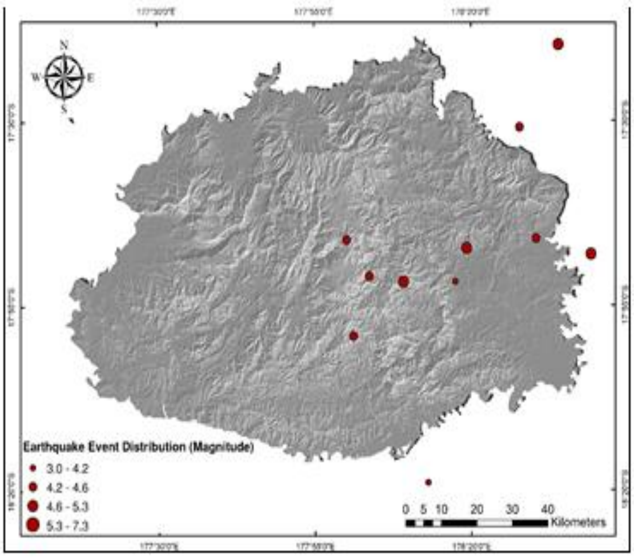

Figure 3.Earthquake event distribution in magnitude for the study area

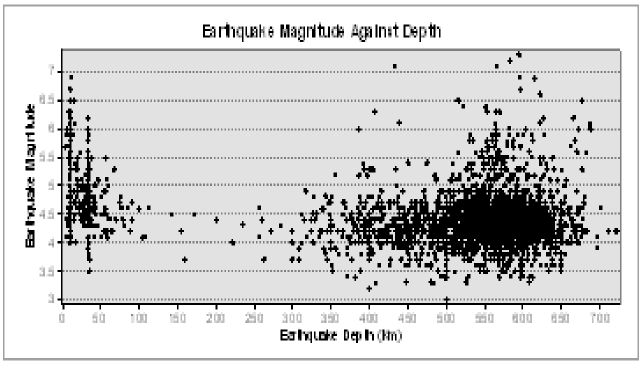

Figure 4. Earthquake magnitude vs earthquake depth

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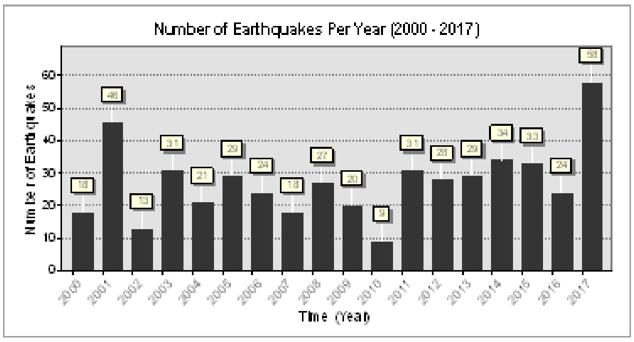

Figure 5. Number of earthquake events per year from 2000 – 2017

Generally, these are historical earthquake data collected for the present study. Apart from earthquake depths, time and magnitudes, Peak Ground Acceleration (PGA) data of 10% gal was also retrieved from Fiji Mineral Resources Department (2015) and USGS (2018).

Landsat 8 OLI (Operational Land Imager) Landsat 7 ETM+ & satellite image (30m spatial resolution – 2016) was extracted from a particular website by the PNG University of Technology IT Department. Fiji shuttle radar topographical mission (SRTM) generated DEM and remote sensing data were two important input data needed to verify and validate ground truth. The Landsat images were georeferenced, mosaicing done, and then ERDAS IMAGINE 8.5 software was used for final sub-setting prior to analysis.

In summary, faultline data and DEM were retrieved from the Fiji Mineral Resources Department and SOPAC for the study area only. Table 1 provides data availability, relevant information and source. The fault line data was in vector shape file (.shp) format and converted to raster for further analysis. DEM was used to create slope through ArcGIS 10.5. Similarly, the soil maps were collected from Fiji Mineral Resources Department and were digitized accordingly in vector format shape file (.shp). Geology map was also digitized and converted to raster format for further analysis. The six layers that were prepared namely lithology, slope, soil average water holding capacity (AWC), soil drainage, soil texture and fault line buffer. Thus, all the data collected were analysed using the Saaty's AHP and incorporated into ArcGIS 10.5.

2.2 Analysis of data layers

Two desired output of the procedures employed here were; a) delineating liquefaction potential zones and b) delineating earthquake hazard zones. In order to produce liquefaction potential zones, different geomorphological data according to terrain and soil attributes, geology data of rock type according to geological formation and fault lines were integrated in the ArcGIS environment. Selected world-wide related publications and research were inquisitively investigated and also sought to understand the procedures well before simulating into this present study.

Six layers were analysed outside ArcGIS environment using the Analytical Hierarchical Process (AHP) also known as Saaty's model gleaned from Saaty (1977, 1980, 1992, 2008). According to Sekac et al. (2016), Multi Criteria Analysis (MCA) technique was proven to be a significant decision support tool for dealing with complex decision constellations where technological, economical, ecological and social aspects are all considered.

For lithology, rock formation was classified under three consolidation categories which were unconsolidated, semi-consolidated and consolidated. Rodda (1974 – 1966) and Hirst (1965) stated that Fiji Islands are composed of only two major consolidation states, which are unconsolidated and consolidated bedrock. Based on this knowledge, weightage and ranking were assigned accordingly in a scale value of '1' which means low potential to value of '4' which means high potential to liquefy during earthquake shaking.

For the three factors related to soil, they were re-classify based on saturation status keeping in mind that unsaturated and soft soils are more prone to liquefaction and can amplify seismic waves resulting in liquefaction. For fault zones, the precept is that area closer to the fault lines have high potential to liquefy during earthquake while potential decreases further away from the fault lines. Fault buffers were created in kilometre (km) interval. According to Pal et al. (2007) and Sekac et al. (2016), fault zones that tend to concede the central tendency of epicentre of earthquake episodes in a tectonically active region. Slope is also considered as an essential component that contributes toward liquefaction during earthquake event. The DEM was extracted and surface tool was employed to generate slope in ArcGIS 10.5.

Each of the six factors was assigned weightage and ranking using the Saaty's model in an excel spreadsheet. The assigned weight and rank was based on different experts' opinions, literature, discussion and publications. In order to be consistent with the weightage and ranking, the pair wise comparison matrix which was designed by Saaty was employed to normalize the weights and identify the consistency ratio. All the normalized weights and rankings were integrated into ArcGIS 10.5 using the raster calculator. Figure 6 below illustrates the methodological step by step approach undertaken and the formula of calculating liquefaction potential zone. The calculation method was adopted from Pal et al. (2007) and Sekac et al. (2016) using the MCA technique in ArcGIS.

The liquefaction potential zone is one of the four layers analysed to produce a final earthquake hazard zones. Seismicity data such as earthquake depths, magnitudes and PGA were extracted, edited in MapInfo Professional 10.0, converted and exported into ArcGIS environment in compatible layers for further analysis. The earthquake data particularly depths and magnitudes were both in point features. Hence, the natural neighbour interpolation tool in ArcGIS was mainly used for this analysis basically because it creates raster surface through averaging the points' value.

For earthquake magnitudes and depths, surface layers were derived by using the natural neighbour interpolation technique while PGA was digitized from a PGA map of Fiji Islands. The earthquake layer was reclassified according to the precept that shallower the depths the more the potential to shake and vice versa. Similarly, earthquake magnitude layer was reclassified based on the precept that lower the magnitude, the lesser the potential to shake and vice versa.

Finally, the PGA layer was digitized, converted to raster layer and reclassified based on the precept that the lower the PGA the lower the potential to shake and vice versa. After preparing all the three seismic thematic layers, the LPZ layer was brought into communion with them and integrated using AHP techniques in excel sheet, the MCA technique in ArcGIS 10.5 was employed to generate the earthquake hazard zones of the study area. All the four factors were assigned weightage and ranking, normalised to ascertain the consistency ratio following the procedures discussed earlier. The summary of all the steps and procedures undertaken in this present study is illustrated in flowchart in Figure 6 below.

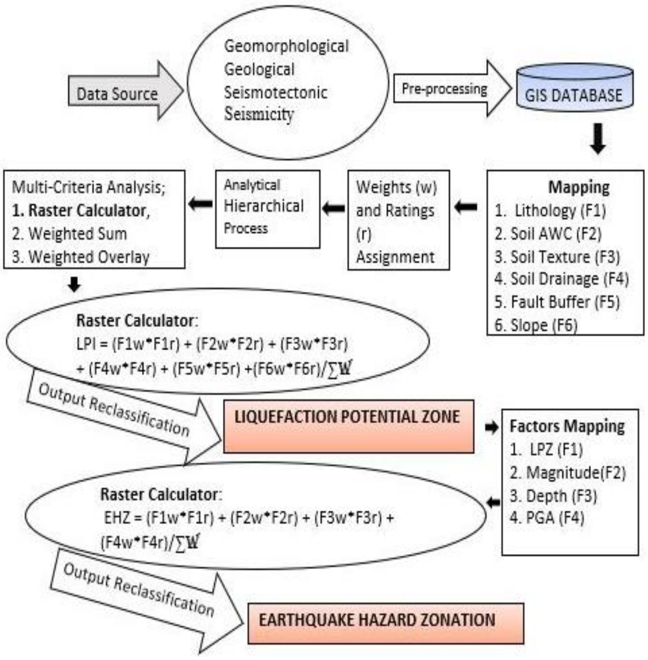

Figure 6. Methodological flow chart

Table 1. Sources of data

Data	Description	Source
Peak Ground Acceleration (PGA%), Fault lines, Folding & Deep strike	Derived from Mineral Resources Department, researchers & New Zealand GNS science	USGS, Fiji Mineral Department & New Zealand GNS science Institute.
Soil factors & Soil Attributes	Derived from Fiji LUP Guidelines & Fiji Soil Classification Map	Fiji Ministry of Agriculture & Mineral Resource Department
Rainfall factors	Derived from Fiji LUP Guidelines	Fiji Meteorological Services
Land Use/Zoning/Built infrastructures Slope	Derived from Fiji Department of Town & Country Planning Derived from SPC	Fiji Department of Town and Country Planning Fiji Mineral Department & USGS
Landsat 8 OLI ETM+& satellite image (30m spatial resolution – 2016)	Downloaded from particular website for verification purposes	PNG University of Technology
Geology (rock type classification)	Derived from Fiji Geology map	Fiji Mineral Resources Department & PNG University of Technology

Moreover, all layers were weighted and ranked according to the AHP processes or Saaty's model based on experts' opinion, good judgement, literature and best practices. It is one of the common methods used to assess, synthesize, analyse and prioritize multiple criteria to achieve a common desirable set of goal. It allows efficient group decision-making, where group members can use their experience, values and knowledge to break down a problem into a hierarchy and solve it by using AHP steps. In this present study, AHP mainly assisted in assigning weightage and ranking within a range of values '1 – 4'. For liquefaction potential zones, a scale value ranges from 1 – 4 were assigned to each individual of the 6 factors accordingly. For example, lithology was categorised into 3 consolidation status; un-consolidation, semi-consolidation and consolidation. In this case, value '1' was assigned to consolidation basically because it does not liquefy during earthquake shaking due to its consolidated characteristics. On the other hand, value '4' was assigned to un-consolidation status basically because of its high potential to liquefy during an earthquake event. This means, during an earthquake event, the seismic wave amplifies when it contacts the un-consolidated geology and may cause surface subsidence under weight. However, the seismic wave strength gets mollified when it contacts consolidation bedrock.

Correspondingly, earthquake hazard was assigned a value range of'1-4'. This means, '1' is low and '4' is high. For example, earthquake magnitude 3 – 4.2 was assigned the value of '1' while magnitude 5.3 – 7.5 was assigned the value of '4' basically because the greater the magnitude, the higher the potential of shaking and vice versa. Sekac et al. (2016) stated that one of the strengths of AHP is that it allows inconsistency while at the same time provides the consistency ratio (CR) to highlight the congruity of consistency not more than the allowable (CR) of >0.10. If the consistency ratio exceeds 0.10 then re-evaluation of weightage is needed. Also, the CR denotes the possibility that the matrix ratings were randomly generated. The normalised weights and assigned weights for 6 factors used for LPZ is shown in Table 3 below while the normalised and assigned weights for 4 factors used for EHZ is shown in Table 5 below.

In respect to liquefaction factors, it is shown that lithology ranked the highest with the normalised weight of 0.383 while slope ranked the lowest with 0.041 as normalised weight. For earthquake hazard, LPZ ranked the highest with the normalise weight of 0.383 while magnitude ranked the lowest with 0.091 normalise weights. The Pair-wise comparison for LPZ is shown in Table 2while Pair-wise comparison for EHZ is shown in Table 4. Finally, after normalizing and being satisfied with the consistency ratio of 0.01 for LPZ and EHZ, the ArcGIS raster calculator was employed to generate the final LPZ and EHZ map for the study area.

III. RESULTS AND DISCUSSION

Liquefaction potential zones were prepared from the 6 thematic layers which were generated from geological and geomorphological data, 6 factors were thoroughly analysed and integrated into ArcGIS environment to produce the liquefaction potential zones. In the same way, the earthquake hazard potential zones were prepared from earthquake historical data. The three seismic layers were earthquake depths, magnitude and PGA. Processing of LPZ and EHZ data underwent a rigorous and dynamic AHP processes before the normalised weights were entered into the ArcGIS 10.5 software, using raster calculator tool to generate the Final earthquake hazard zones for the study area. Multi Criteria Analysis has been widely employed in various fields of disaster risk reduction to analyse phenomenon such as flooding, soil erosion, ground water assessment to name a few and it was also employed in this present study.

3.1 Assessments for liquefaction potential zones (LPZ)

Researchers such as Green et al. (2013), Koulali et al. (2015) and Pal et al. (2007) pointed out that soils with loose consistency or quick sand easily got fluid nature and disaggregated during earthquake event, this is simply known as liquefaction. These researchers revealed that unconsolidated particles have high potential to liquefy or separated from another during earthquake shaking. The 6 LPZ factors were; lithology, soil texture, soil AWC, fault zone, soil drainage and slope. Table 2 highlighted the pair-wise comparison applied to each factor.

Table 2. Pair wise comparison matrix for LPZ

	Lithology	Soil Texture	Soil AWC	Fault Zone	Soil Drainage	Slope
Lithology	1	2	3	4	5	6
Soil Texture	1/2	1	2	4	4	5
Soil AWC	1/3	1/2	1	2	3	4
Fault Zone	1/4	1/3	1/2	1	2	3
Soil Drainage	1/5	1/4	1/3	1/2	1	2
Slope	1/6	1/5	1/4	1/3	1/2	1

For lithology, Davis (1954) and Andrew (2005) revealed that unconsolidated sediments have a tendency to amplify seismic waves and are prone to liquefaction whereas the consolidated sediments or rock types do not amplify seismic waves, rather reducing the intensity of seismic wave's propagation. In light of the above precept, the weightage and ranking for each factor was assigned accordingly. The New Zealand Soil Bureau (1960) revealed that Fiji's geology is classified into two (2) consolidation statuses which are Consolidated and Unconsolidated bedrocks. Hence, Geobook (2009) further confirmed the bedrock of Fiji by characteristic geological classes with respective consolidation status. In-depth research regarding Fiji's geology has been scanty. However, existing publications and research carried out by Seeley et al (1970) and Rodda (1974 – 1966) re-confirms the accuracy of the initial study by the New Zealand Soil Bureau (1960) regarding the types of Fiji's geology. Based on this precept, the weightage and ranking assigned and thematic layer prepared as shown in Figure 6 below. Table 3 illustrates the normalised weights and raking for all 6 factors with a consistency ratio of 0.01.

Table 3.Normalised and assigned weights for 6 factors used for LPZ

Factors	Normalize weights	Assigned weights
Lithology	0.383	6
Soil Texture	0.250	5
Soil AWC	0.161	4
Fault Zone	0.091	3
Soil Drainage	0.071	2
Slope	0.041	1
Total	**1**	
Consistency Ration (CR) = 0.01		

Table 4. Pair wise comparison matrix for EHZ

	LPZ	PGA	Depth	Magnitude
LPZ	1	2	3	4
PGA	1/2	1	2	3
Depth	1/3	1/2	1	2
Magnitude	1/4	1/3	1/2	1

Table 5.Normalised and assigned weights for 4 factors used for EHZ

Factors	Normalize weights	Assigned weights
LPZ	0.383	4
PGA	0.250	3
Depth	0.161	2
Magnitude	0.091	1
Total	**1**	
Consistency Ration (CR) = 0.01		

The EHZ pair wise comparison as shown in Table 4 revealed that LPZ was assigned with highest rank while magnitude ranked the lowest. The EHZ assigned and normalised weights as shown in Table 5 revealed the consistency ratio of 0.01. LPZ has a normalised weight of 0.383 while magnitude has a normalise weight of 0.092.

Soil classification based on infiltration rate was derived from USDA (1975) soil taxonomy and cross checked with Fiji's soil classification derived from Fiji Ministry of Agriculture Soil Land Use Capability Classification System Guideline. Soil is classified under four (4) Hydrologic Soil Group (HSG) which is A, B, C and D according to its texture as illustrated on Table 6 below. Group 'A' soil has the highest infiltration rate while Group 'D' has the lowest. In other words, Group 'D' has high run-off compare to group 'A' soil. Hence, high water infiltration in the soil makes it easy to liquefy during an earthquake event. Therefore, sand, loamy sand and sandy loam soils have high potential to liquefy during earthquake shaking compared to group 'D'.

Table 6.Classes for HSG

HSG	A	B	C	D
Soil Texture	Sand Loamy sand/Sandy loam	Silt Loam/Loamy soil	Sandy Clay Loam	Silty Clay Loam Sandy Clay Silty Clay Peat

Soil available water holding capacity (AWC) reveals the potential of soil to store water at a certain period of time. Soil group 'A' have high water holding capacity compared to soil group 'D' which have low water holding capacity. Sekac at al. (2016) stated that if there is very low available water holding capacity in the soil, then there is no chance of liquefaction however liquefaction during earthquake is possible if the amount of water capacity is more in the soil.

Soil drainage is paramount to ascertain the drainage potential of soil. Soil drainage data was derived from the Fiji Ministry of Agriculture Land Use guideline and digitize to reflect the study area. It is ascertained that water logged soil has a very high potential to liquefy during earthquake shaking basically because of the amount of water the soil stores. Table 7 showed the assigned weightage and thematic map shown in Figure 7.

Fault, lineaments and other geological structure were also taken into consideration. These zones were delineated and buffering technique was applied to identify area prone to liquefaction. Obviously, earthquake occurs along fault lines. Proximity to fault lines was calculated, using the multi ring buffer to indicate four zones of severity. Hence, further the distance from the fault line the lesser is the potential of liquefaction while closer the distance the higher is the liquefaction potential. Table 7 showed the assigned weightage and thematic map shown in Figure 7.

Slope was another essential contributing factor of liquefaction zone that was also considered. The steepness of the slope determines the potentiality and tendency of liquefaction. For example, a flat land has very low liquefaction potential compare to a steep hill. The slope gradient contributes to the velocity of surface water run-off. Surface water flows gently on gradual to flat rolling hill with low force compared to steep hill and cliffs. Table 7 showed the assigned weightage and thematic map shown in Figure 7

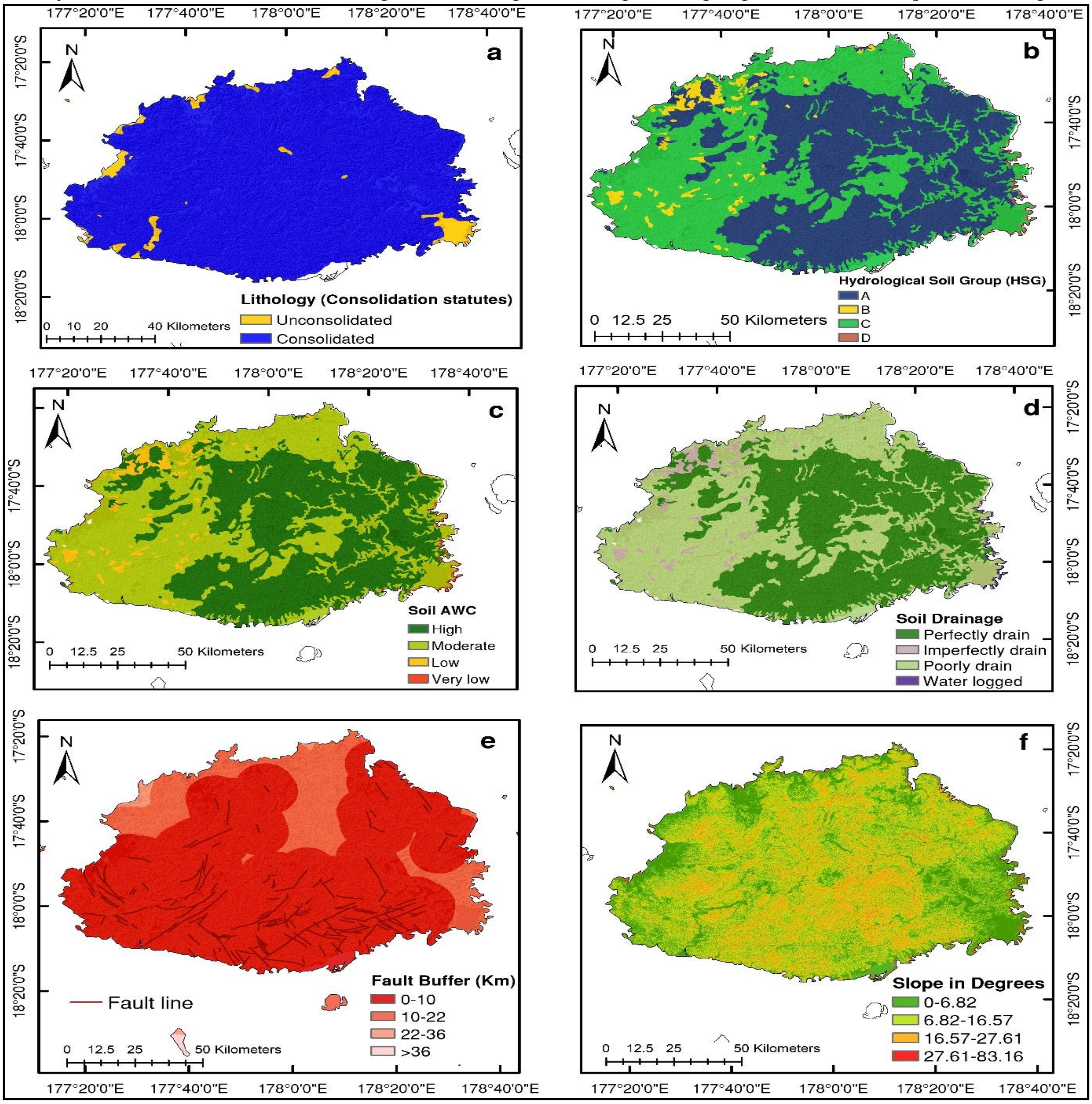

Figure 7. Thematic mapping of the 6 factors for liquefaction potential zone; a lithology in consolidation status, b hydrological soil group, c soil available water holding capacity, d soil drainage, e fault buffer in kilometres and f slope in degrees

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Furthermore, lithology has a normalised weight of 0.383, the consolidated class covers 96.63% while unconsolidated class covers only 3.25% of the study area. Soil texture has a normalised weight of 0.025, whereby group 'A' covers 49.17% while group 'B' covers 3.03% of the study area. Soil AWC has a normalised weight of 0.161, whereby 49.17% area coverage was relatively 'high' while 0.68% area coverage was relatively 'low'. Fault buffer has a normalised weight of 0.104, whereby 89.3% area coverage was relatively within '0 – 10' kilometres from the fault lines associated with high risks. Soil drainage has a normalised weight of 0.091, in which 49.17% area coverage was 'perfectly drained' associated with less risk to liquefy during an earthquake event. Slope has a normalised weight of 0.071, whereby 84.01% area coverage was relatively 'flat to gentle' slope and less risk to liquefy during earthquake shaking. Table 7 illustrates the assigned weights, areas and percentages of the 6 LPZ factors.

Table 7.Ranking/rating and normalised weightage for LPZ

Theme	Weight	Classes	Ratings	Normalize rate	Area (KM Sq)	Area (%)
Lithology (GE)	0.383	Consolidated	1	0.16	823.29	96.63
		Semi-consolidated	3	0.29	0	0
		Unconsolidated	4	0.53	270.1	3.25
Soil Texture (ST)	0.25	A	4	0.46	418.93	49.17
		B	3	0.27	250.85	3.03
		C	2	0.16	401.98	47.18
		D	1	0.09	5.86	0.68
Soil AWC (SA)	0.161	A - High	4	0.53	418.93	49.17
		B - Moderate	3	0.29	401.97	46.47
		C- Low	2	0.16	310.71	3.71
		D – Very low	1	0.09	25.85	0.68
Fault Buffer (FB) (km)	0.104	>36	1	0.09	17.19	1
		22 - 36	2	0.16	700.12	0.4
		10.0-22.02	3	0.27	146.43	9.15
		0-10	4	0.46	142.84	89.3
Soil Drainage (SD)	0.091	Perfectly drain	1	0.09	418.93	49.17
		Imperfectly drain	2	0.16	250.84	3.03
		Poorly drain	3	0.27	401.97	47.18
		Water logged	4	0.46	5.87	0.68
Slope (SP) (degree)	0.071	0-6.82	1	0.09	347.5	84.01
		6.82-16.57	2	0.16	443.6	107.26
		16.57-27.61	3	0.27	234.3	56.65
		27.61 - 83.16	4	0.46	85.2	2.06

In ArcGIS 10.5, raster calculator tool, a following formula was employed which was gleaned from Pal et al. (2007) and Sekac et al. (2016) to calculate the final liquefaction potential zones.

GeoHazards Index (GHI) = [(GEw.GEr) + (STw.STr) + (Saw.SAr) + (FBw.FBr) + (SDw.SDr) + (SPw.SPr)]/∑w

Table 8 below showed a Geo-Hazard Index value (GHI) as a result of integrating the 6 thematic factors in ArcGIS 10.5. GHI further reclassified into 3 classes to show only three zones which were; 'Low' zone with 55.5% area coverage, 'Moderate' zone with 41.31% area coverage and 'High'zone with 3.18% area coverage. Micro details were provide in Table 8 below.

Table 8. LPZ index and zones information

Geohazard Index (GHI) Value	Liquefaction Potential Zones (LPZ)	Area (Sq. km)	Area %
1.0 – 2.0	Low	541.93	55.5
2.0 – 3.0	Moderate	403.32	41.31
3.0 – 4.0	High	310.0	3.18

Finally, the ultimate thematic LPZ map shown in Figure 8 below was successfully generated through inquisitorial interrogating the 6 factors using the AHP and MCA in ArcGIS. It provides a visual and readable solution to disaster risks reduction, disaster risk management and monitoring in urban and regional physical planning fields. It informed decision makers, planners, policy makers, law enforcers and the general public of Fiji Islands to understand the potentiality of liquefaction at various categories during an earthquake event in VitiLevu Island.

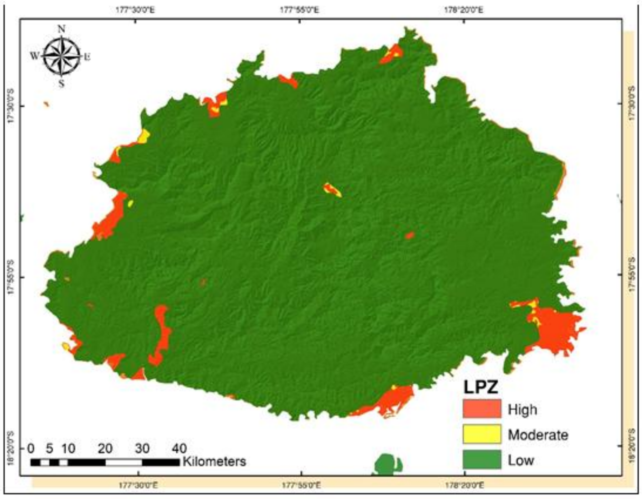

Figure 8. Liquefaction Potential Zones of VitiLevu Island

3.2 Assessments for earthquake micro Zonation (EHZ)

Identifying earthquake hazard zones is essential to engineering fields for infrastructural design, policy makers and the general public. People need to be informed regarding the vulnerability of their residential and work areas, infrastructural assets along with the ambience in regards to earthquake shaking. Seismic data were derived from the Fiji Mineral Resources Department (2015) and USGS (2018) mainly earthquake depths, magnitude and Peak Ground Acceleration in 10% gal. For earthquake magnitude, points were downloaded from USGS and interpolation was carried in ArcGIS. High magnitude has great influence to liquefy loose particles or unsaturated surface. For example, a 7.3 magnitude has more destructive power than a 3-magnitude earthquake. Upon this knowledge, the weightage and ranking were assigned accordingly as shown in Table 9 below. The magnitude ranges from 3 to 7.3 for this present study as shown in Figure 9. Earthquake magnitude has the normalised weight of 0.095 which was the least of the four EHZ factors.

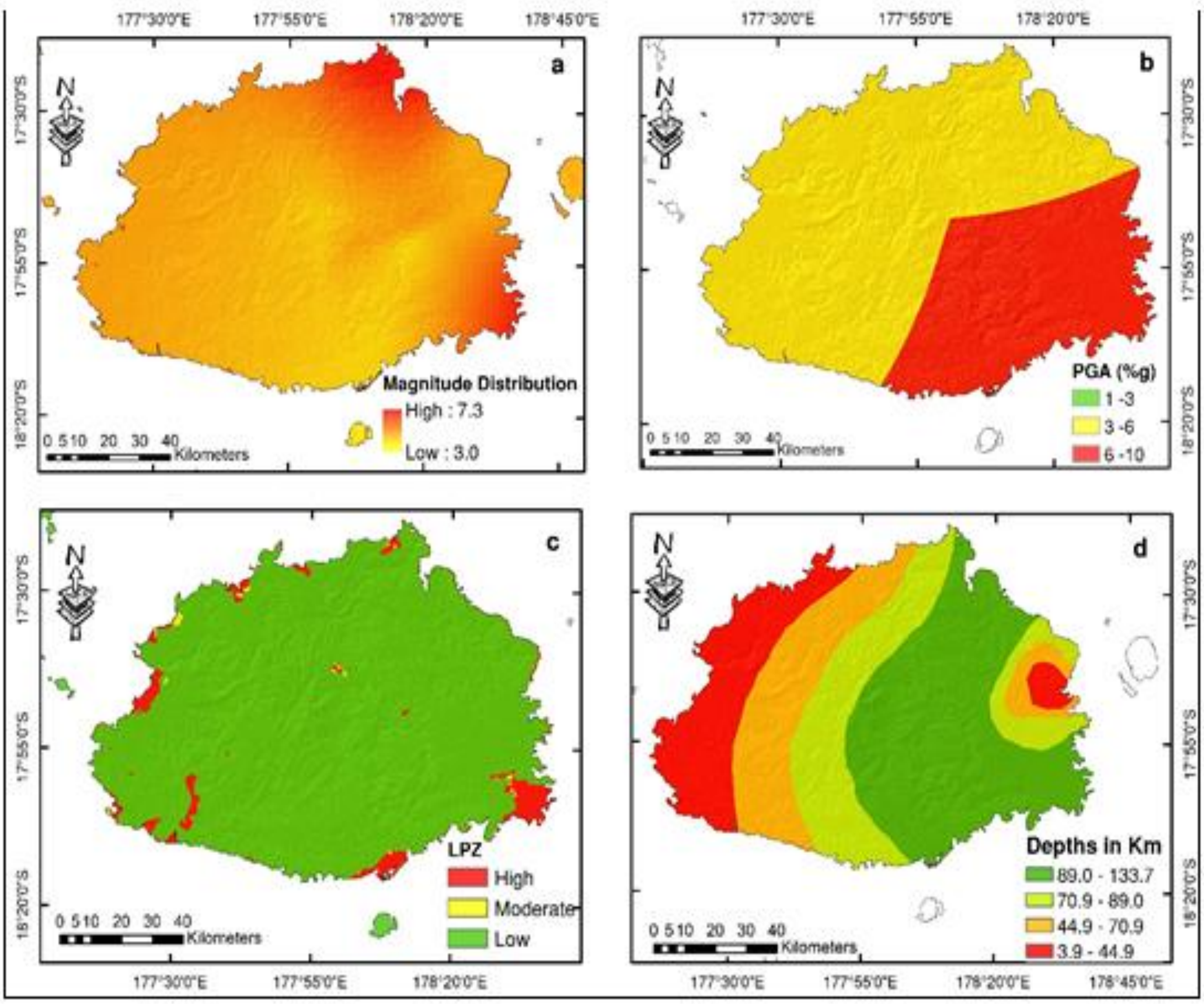

Figure 9. Four factors of EHZ; a earthquake magnitude distribution, b peak ground acceleration in 10%gal, c liquefaction potential zone, d earthquake depths in kilometres.

Similarly, earthquake depth was downloaded from USGS (2018) and interpolated using the natural neighbour tool in the ArcGIS environment. The depths range from 3.9 to 133.7 kilometre with the normalised weight of 0.160. Weightage and ranking were assigned according to the precept that shallow depth tremors have high potential to liquefy compared to areas of high depth ones. Seismic waves are very likely to amplify and increase its dwelling time in shallow depths which can cause lethal destruction if it comes into contacts with the unsaturated or loosed surface. On the other hand, higher depths pose low potential to liquefaction during earthquake events due to the longer distance and travelling time of the seismic waves attenuating its strength. Table 9 revealed that earthquake depths of 89 – 133.7 km have 39.55%area coverage contrary to earthquake depths of 3.9 – 44.9 km which has 18.34% area coverage. Hence, earthquake depth thematic layer was prepared using the AHP process and MCE in ArcGIS to delineate four zones of low to very high depths.

Table 9. Weightage and ranking for each factor assessed for earthquake hazard Zonation

Theme	Weight	Classes	Ratings	Normalize rate	Area (KM. Sq.)	Area (%)
LPZ	0.466	Low	1	0.06	497.48	50.95
		Moderate	3	0.09	447.77	44.49
		High	4	0.16	31.05	3.18
PGA (%gal)	0.277	1-3	1	0.06	121.36	10.52
		3-6	3	0.09	682.45	59.2
		6-10	4	0.16	348.92	30.26
Earthquake Depth (ED) (km)	0.160	3.9 -44.9	4	0.41	189.29	18.34
		44.9 - 70.9	3	0.26	204.99	19.87
		70.9 - 89.0	2	0.15	229.26	22.22
		89.0 - 133.7	1	0.09	408.022	39.55
Earthquake Magnitude (EM)	0.095	3-4.2	1	0.06	634.50	35.14
		4.2-4.6	2	0.09	129.16	7.15
		4.6-5.3	3	0.16	181.94	10.07
		5.3-7.3	4	0.26	859.62	47.61

Peak Ground Acceleration (PGA) of 10% was derived from USGS (2018) and cross checked with Fiji Mineral Resources Department (2015), it has the normalised weight of 0.277. PGA was reclassed into three categories within 1 – 10% as shown in Table 9 using the AHP on the excel spreadsheet. Then, normalised weights were entered into ArcGIS 10.5 to delineate three zones of shaking as shown in Figure 9. The precept is that, the higher the percentage of shaking the more potential of liquefaction when seismic waves come in contact with loose or unsaturated sub surface. Hence, 1-3 %gal comprised of 10.52% area coverage, 3-6 % gal comprised of 59.2% area coverage and 6-10 %gal comprised of 30.26% area coverage. All categories were reclassed and combined using MCA to provide a PGA thematic map as shown in Figure 9.

Moreover, LPZ was assigned a normalised weight of 0.466 with three classes delineating 'low' to 'high' liquefaction potential zones. It is the most influential layer which was derived from the 6 factors as discussed earlier.The AHP technique was used to assign weights and ranking to individual factor. It can be seen from Table 9 that value '1' was assigned to the least contributing factor and '4' to the most contributing factor. The table also showed the area in kilometre square (km2) and percentages (%) for each class of the themes.

Table 10. Earthquake hazard levels re-classification

Earthquake Hazard Index (EHI)	Earthquake Hazard Zones (EHZ)	Area (Sq. km)	Area %
1.27 – 1.87	Low	541.3	53.18
1.87 – 2.42	Moderate	350.1	34.37
2.42 – 3.55	High	120.7	12.43

Finally, all the four factors namely LPZ, PGA, earthquake depths and magnitude were integrated into the ArcGIS environment, using the raster calculator technique in the map algebra toolbox.The formula was gleaned from Pal et al. (2007) and Sekac et al. (2016) commonly used for this present study is shown below;

Earthquake Hazards Index (EHI) = [(LPZw.LPZr) + (PGAw.PGAr) + (EDw.EDr) + (EMw.EMr)]/∑w

The EHZ layer was further reclassified into three earthquake hazard zones for the study area. The zones are; 'low' which comprised of 543.3 (km2) area coverage and consists of 53.18%, 'moderate' which comprised of 350.1 (km2) area coverage and consists of 34.37% and 'high' which comprised of12.7 (km2) area coverage and consists of12.43% of the total study area land mass. Hence, Figure 10 presents the final earthquake hazard Zonation map of VitiLevu Island.

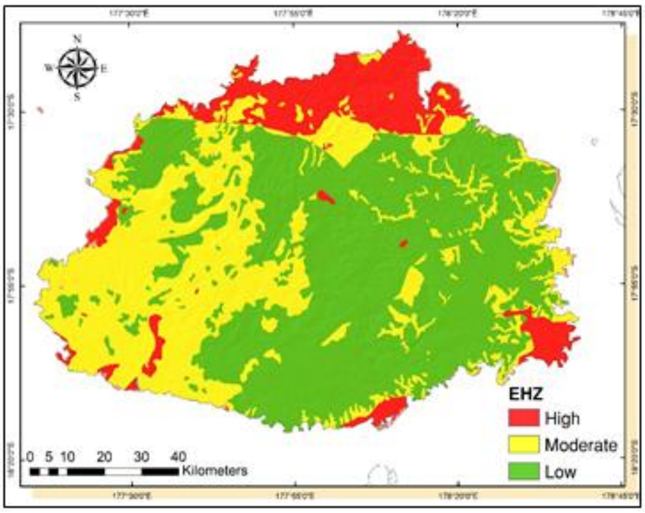

Figure 10. Final earthquake hazard zonation map of VitiLevu Island

3.3 Evaluation of infrastructures and hazard zones

Built infrastructures were overlaid on the liquefaction potential zones' layer and assessed accordingly as shown in Figure 11. The present study revealed the following results for each zone; 'low' zone comprised ofa wharf (Suva wharf), 319.1 km road length and 7 hospitals, 'moderate' zone comprised of 5 towns and cities and 5.5 km road length, and 'high' zone comprised of 6 towns & cities, 2 airports, 1 sea port, 38.84 road length and 4 hospitals. Table 11 below provides micro details of LPZ infrastructure assessments.

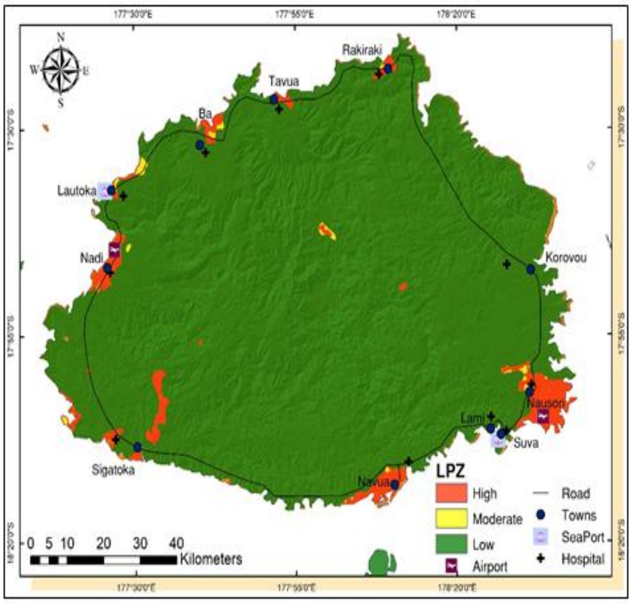

Figure 11.Features assessed under liquefaction potential zones (LPZ)

Table 11. Built up infrastructure assessed under each liquefaction potential zones (LPZs)

VITI LEVU ISLAND	LIQUEFACTION POTENTIAL ZONES		
	High	**Moderate**	**Low**
Towns & cities	Nausori Navua Sigatoka Nadi Lautoka Rakiraki	Suva Lami Ba Tavua Korovou	-
Airports	Nausori airport Nadi International airport	-	-
Sea ports	Lautoka wharf	-	Suva wharf
Main Road (km)	38.84	5.5	319.1
Hospital & Health centres	Nausori Sigatoka Nadi Rakiraki	-	Tavua Ba Lautoka Navua Lami CWM Korovou

Similarly, built infrastructures were overlaid on earthquake hazard zones layer and assessed accordingly as shown in Figure 12. The present study revealed the following; 'low' zone comprised of 113.7 km road length, 'moderate' zone comprised of 4 towns& cities, 1 sea port, 82.1 km road length and 6 hospitals & health centres, and 'high' zone comprised of 7 towns & cities, 2 airports, 1 sea port, 110.1 km road length and 5 hospitals. Table 12 provides micro detail EHZ assessment of the study area.

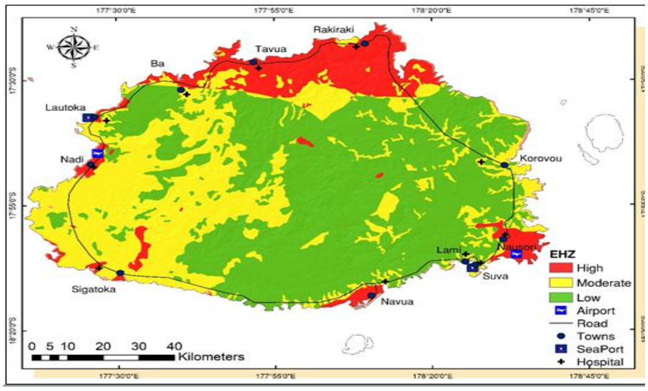

Figure 12. Features assessed under earthquake hazard zones (EHZ)

Interestingly, the present study revealed that LPZ and EHZ have high congruity on hazards assessments. For example, LPZ indicated that 6 towns &citieswere located within the 'high' zonewhereby EHZ revealed that 7 towns &citieswere located on the 'high' zone. Thus, it is important to understand the zones of vulnerability during an earthquake event in order to mobilize our resources before and after an earthquake disaster VitiLevu Island.

Table 12. Built up infrastructure assessed under each earthquake hazard zones (EHZs)

VITI LEVU ISLAND	EARTHQUAKE HAZARD ZONES		
	High	**Moderate**	**Low**
Towns & cities	Nausori Navua Sigatoka Nadi Lautoka Tavua Rakiraki	Korovou Suva Lami Ba	-
Airports	Nausori airport Nadi international airport	-	-
Sea ports	Lautoka wharf	Suva wharf	-
Main Road (km)	110.1	82.1	113.7
Hospital & Health centres	Nausori Sigatoka Nadi Tavua Rakiraki	Suva Lami Lautoka Ba Korovou Navua	-

This research further validates the study by Vanualailai (2008) who revealed that 90% of Fiji's public infrastructure is located in the coastal area. In Lieu of other natural disasters, earthquake hazard zones are demarcated as high on the coastal zones particularly on the locality of major towns and cities. In addition, uneven population distribution makes it worse as more than 60% dwells within the urban zones which are associated with natural hazards.

However, there are structural and non-structural measures that could be employed to enhance natural disaster preparation and ensure effective post recovery. Structural or engineering measures such as sea walls, revetment, dykes and sea break are costly and expensive to construct for small economy such as Fiji Islands. Non - structural measures such as building and construction codes, hillside development policies, hazard zone maps and tax incentives are affordable and pragmatic in a sense of formulation and implementation. Hence, non-structural measures mean dynamic, vibrant and buoyant in spatial planning in order to reduce the risks of natural hazards.

IV. CONCLUSION AND RECOMMENDATION

Earthquake hazard zonation and assessment for Fiji Islands is paramount in this current age in order to protect the lives of some 884,887 strong population, reducing the risks of disaster and implementing dynamic planning policy to ameliorate the country's disaster resiliency and management. According to the historic earthquake data retrieved for this study, Fiji Islands has never recorded an eight-magnitude earthquake until to date. However, it does not rule out the possibility of severe destruction which may instigated by 7 or less earthquake magnitude basically because nature has its own course as proven by the 6.5 magnitude in 1953, known as Suva earthquake. GIS based decision making is widely used and proven to be an effective scientific and engineering tools to provide visual and readable solution for disaster risks reduction and proper preparedness.

Urban planners, who are at the forefront and first line of defence in combating and reducing disaster risks should be enlightened of the implementation of GIS environment in assisting and supporting decision making. Hence, a collaborative taskforce is warranted to spearhead research on hazards mapping and simulate solutions using technology such as ArcGIS for the country. This present study revealed the urgency to disseminate and share knowledge across the government sectors, non – government sectors and the general public about the potential disastrous impact of earthquake hazards on major areas in VitiLevu Island.

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