Landslide risk mapping using Geographical Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA)

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Abstract

Landslides have frequently occurred in several hilly settlements all over the world causing a great impact on life and the economy at large. The uncertainty of their occurrence has continued to hurdle mitigation and response mechanisms in landslide-prone areas. Attempts have been made in recent years to predict them and to warn concerned authorities thus providing decision makers a good overview for mitigation, planning, response and recovery for areas at risk. In consideration of elements of the environment affected by the magnitude of landslides, this paper discusses the application of Geographical Information System (GIS) and Multi-Criteria Decision Analysis (MCDA) approach to mapping the extent of landslide hazard risk. Using Somerset county in South-West England as a case study, landslide hazard indicators (lithology, slope, and water level in the rocks by the rainfall event) and landslide vulnerability indicators (population, buildings, transportation, and green area) were in each aspect combined after multicriteria decision analysis to derive respective hazard index map and the landslide vulnerability index map. The resultant landslide risk index map derived as the product function of the susceptibility index and vulnerability index gives the representation after reclassification, the final landslide risk map is classified into indicative classes of high (99%) moderate (0.5%) and low (0.5%) showing the level of landslide risk in the study area.

Key Words: GIS, MCDA, Landslide Hazard, Landslide Vulnerability, Landslide Risk, Mapping

1 Introduction

Identification of landslide and creation of landslide risk maps are significant efforts that support several environmental planners, local administrations, and decision-makers in landslide disaster planning and management. The accuracy of landslide risk maps is crucial for mitigation measures that would reduce the loss of life and property. Today, models being used for landslide risk mapping necessitate the combination of several factors describing characteristics of the terrain, meteorological and social-economic conditions (Taskin Kavzoglu et al., 2013). It's in the past decade that landslide risk mapping and assessment has been receiving good attention by the international scientific community (van Westen et al., 2005). A paper written by Varnes (1984) gives one of the top practical definitions of risk as "the estimated number of lives lost, people harmed, destruction to property and distraction of economic activity caused by a certain destructive phenomenon for a particular area and specific period." When assessing physical losses, risk can be evaluated as a function of vulnerability, the quantity of the aspects at risk and the probability that a given hazard event would occur with a given enormity/intensity (van Westen et al., 2005). A number of methodologies have been proposed for largescale landslide risk mapping such as for entire countries, however, the aim of undertaking landslide risk assessment at small scales aids the production of a landslide risk index that makes it possible to easily identify and map high-risk regions for more detailed analysis and studies (Abella et al., 2007). Risk indexes have been utilized in several small-scale landslide risk assessments for either specific countries or at a global level (Evans and Roberts 2006). The results are risk maps that support government decision-makers in prioritizing funding and efforts for risk assessments at various national levels as well as developing early warning systems for landslide occurrence. Landslide risk mapping has been mainly limited by the unavailability and undetailed data and thus the application of deterministic landslide hazard assessment methods (Varnes 1984) may not be effectively applied. Given the data limitations, Multi-Criteria Decision Analysis (MCDA) approaches in a Geographic Information System have been utilized in several studies to derive qualitative landslide risk indexes that have supported landslide risk mapping (Abella et al., 2007). At the most primary level, GIS-MCDA can be explained as "a collection of processes that combine and transform geographical information and the decision-maker's preferences to achieve value knowledge for decision making. Disaster management assessment is one area that significantly requires the application of GIS-MCDA, this is because GIS-MCDA provides powerful methods that support the analysis and modeling of both current and future hazards (Feizizadeh et al., 2013). The primary goal in MCDA is aimed at developing ways of combining information from several factors or criteria to form a single index of evaluation (Ladas et al., 2007). The GIS-MCDA approach has in the past been widely used for landslide hazard mapping and zonation since it facilitates the integration of distinct GIS data layers with distinct levels of uncertainty. Based on this, this study employed Multicriteria Decision Analysis (MCDA) and GIS for the preparation of the landslide risk map for the Somerset county in England. Using the approach defined in (Wisner et al., 2016) for disaster risk as a function of the product of hazard (susceptibility) and Vulnerability in the study area, MCDA was employed to produce hazard and vulnerability index maps from carrying out multicriteria analysis of factors and aspects selected on the basis of their influence or proneness to landslide occurrence in the study area. The final map after reclassification represents the final land risk map of the study area. The objectives of the study are summarized below;

- Analyzing landslide hazard
- Analyzing different landslide vulnerability
- Producing a landslide risk index map for the study area

2 The Study Area and Data Used

This study covers landslide events that have occurred in the period (1952-2014) in Somerset county located in the South West of the United Kingdom. Somerset County is situated at 51^0 06'N, 20 54'W having a total area size of 4,171 km^2 and an estimated population of 965424 people. According to the British Geological Survey (BGS), Somerset county has suffered from several mass movements and landslides, with the national landslide database enlightening that a total of 448 landslides have happened in the county from 1952 to 2014 (Figure 1). Landslides are described by BGS.ac.uk (2016) as the movement of a mass of rock, earth or debris down a slope and landslides can occur in a varied environment typified by steep or gentle slope gradients from mountainous arrays to coastal cliffs. In South-west England, landslides are experienced at both the coastal lands and inlands as can be seen in the landslides inventory Map Figure1. The occurrence of landslides has been reported by the British Geological Survey (BGS) to be due to combination factors including:

- The presence of cliffs along the coast insinuating a rapid change in elevation and steep slope angles.
- The cliffs create great exposure of rock and to erosive and weathering processes.
- Increased weathering and earth surface undercutting as a result of inland and coastal processes.

The data used for landslide hazard indicators were obtained from the British Geological Survey (BGS) while the data for vulnerability indicators were obtained from Ordinary Survey UK with the Population data obtained from UK Data Service Census Support.

Table 1. Data sources

Data	Source
Landslides Hazard Map	British Geological Survey.
Population	UK data Service Census Support
Roads	Ordinary Survey UK
Buildings	Ordinary Survey UK
Green Area	Ordinary Survey UK

Figure1 below shows the map of England and its counties with Somerset county distinguished on the left and the extracted Somerset county on the right showing landslide locations.

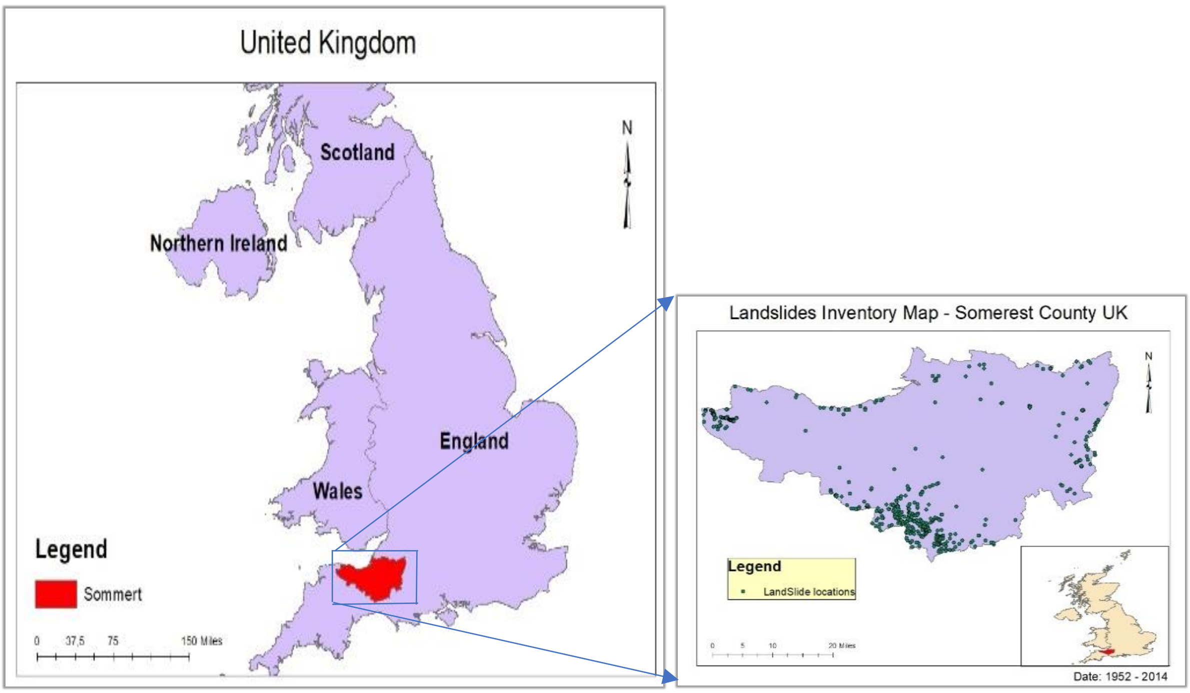

Figure 1. Showing the map of England and its counties with Somerset county distinguished on the left and the extracted Somerset county on the right showing landslide inventory map (landslides locations)

3 Methodology

Multi-criteria decision analysis (MCDA) integrated with GIS has been widely used in disaster management analysis, and MCDA provides different techniques and procedures to analyze several geohazards such as landslides, supporting the production of landslide susceptibility maps (hazard maps) and risk maps (Feizizadeh et al., 2013). The production of Landslide risk maps requires a selection group of indicators, followed by the application of different methods to standardize and weight the indicators in order to structure the criteria to use MCDA (Abella et al., 2007).

Basing on the fact that we were challenged by the unavailability and undetailed data to undertake a conclusive risk assessment, a semi-quantitative approach was selected since it's relevancy analysis based (Mika Marttunenab et al.,2019). The key difference between qualitative and semi-quantitative approaches is the allocation of weights to contributing factors under a predefined criterion. The semi-quantitative valuation for landslide risk analysis is regarded as an important approach given a scenario where the likelihood of gathering numerical data is challenging in the initial planning process to assess hazards and risks (Australian Geomechanics Society and Sub-committee on landslide risk management 2000). A very illustrative semi-quantitative approach was the ranking method applied to develop a risk classification system for cut and fill slopes and for natural slopes to identify suitable areas for future development in Hong Kong (Koirala et al., 1988).

Semi-quantitative risk assessment is used to analyze landslide risk and to estimate the level of landslide risk in the form of map representation. A semi-quantitative scoring system provides a middle level between qualitative and quantitative assessment in the index scale (Sumner et al., 2002). A Semi-quantitative method is useful to give an initial picture of the risk especially when there is a lack of numerical data, by giving scores for each indicator to assess the occurrence of the damage (Abella et al., 2007). The risk map for each pixel is provided by multiplying the hazard index by vulnerability index Eq. 1 (Varnes 1984, Wisner et al., 2016).

$$\text{Risk Index} = \text{Hazard index} \times \text{Vulnerability index} \qquad \text{(Eq. 1)}$$

The above equation is also well described by (Wisner et al., 2016) were they define Disaster Risk = Vulnerability x Hazard. Risk is a combined function of vulnerability and hazard, and its relationship is indicated as an outcome of multiplication between hazard and vulnerability. The risk index will be high when both hazard and vulnerability are high. In this study, the hazard index represents the probability of landslide occurrence after combining three different factors triggering landslides represented by slope stability, lithology, and precipitation. The Vulnerability index was obtained after a combination of four different vulnerability factors of population, transport, green areas, and buildings.

The implementation of the semi-quantitative method was done in ArcGIS, a group of indictor maps was used to represent the spatial criteria. All the indicators were ranked and weighted depending on the importance of the indicator, and the values of the indicators were normalized to put them on the same scale using a minimum-maximum scale [0,1].

The vulnerability indicators were weighted using the rank order centroid method for multicriteria evaluation described in (A. Touran et al.,2009; J. Barry Barker et al.,2009). The authors provide several weighting methods for multicriteria evaluation including (Delphi Method, Rank order Centroid, Ratio method, and pairwise comparison). The fact that we did not have enough information such as stakeholder judgments or preferences and expert subjectivity in undertaking this study, only the Rank order Centroid method provided the best approach to deriving weights since it uses the ranking of factors as inputs to determining weights and the ranks usually reflect the importance of the indicators. The Pairwise comparison method for weighting the indicators is widely used in studies and literature to evaluate the relative importance between every two indicators, and this often requires experts in this field to give their perception. Therefore, as an effort to determine the ranking of indicators, we carried out an assessment and review of various related literature in order to discover and assess how most studies applied weighting criterion to related indicators and this formed basis of ascertaining their importance level thus determining the ranking of indicators considered in this study. Ranking the factors was ascending meaning that the highest weighted indicator is the most important indicator considered in reviewed literature and is given a rank number 1. Basing on the analysis obtained from the literature review and looking at the vulnerability indicators considered, the population was given the highest eminence and hence given a rank of 1 and the least regarded was the green area indicator which gets a rank of 4.

After ranking, the weights for each indicator were derived using the rank order centroid method (Eq.2); this method does not depend on the subjectivity and judgment when assigning the weights. It's a simple method for assigning weights to several items ranked according to their importance (A. Touran et al.,2009; J. Barry Barker et al.,2009). This method uses the ranks as inputs to transform them into weights for each item. The conversion or transformation is based on the formula given in (Eq.2)

$$W(i) = (\frac{1}{M}) \sum_{n=1}^{M} (1/\mathrm{n}) \qquad \text{(Eq.2)}$$

Where M is the number of indicators, n is the rank of the indicator and W is the weight for (i) indicator. Using (Eq. 2) considering that we have four indicators; Population being the indicator ranked as first will be weighted as (1 + 1/2 + 1/3 + 1/4) / 4 = 0.52, the second (Building) will be weighted as (1/2 + 1/3 + 1/4) / 4 = 0.27, the third (Transportation) will be weighted as (1/3 + 1/4) / 4 = 0.15, and the last (green area) will be (1/4) / 4 = 0.06. Table (2) explains the ranks of the vulnerability indicators and their weight values.

Table 2. Vulnerability indicators; their ranks with weight values using the Rank Order Centroid.

Vulnerability Indicator	Rank	Weight
Population	1	0.52
Building	2	0.27
Transportation	3	0.15
Green Area	4	0.06

After determining weights, weighted overlay analysis was done in ArcGIS software, and all the four layers of vulnerability indicators are used. The Weights derived in table 2 are assigned to the layers with respect to their ranks thus producing the composite vulnerability index map.

The methodology model in figure 2 below gives an overview of components contributing to the production of the landslide risk index map. As can be seen, the model shows the selection of risk indicators (vulnerability and Hazard indicators) indicating that socio-economic conditions are the main sources for vulnerability indicators while the landslide inventory combined with triggering factors are the main sources of hazard indicators. This is followed by the structuring of criteria and then selection of standardization and weighting approaches that lead to the creation of composite maps that are integrated to produce the landslide risk index map.

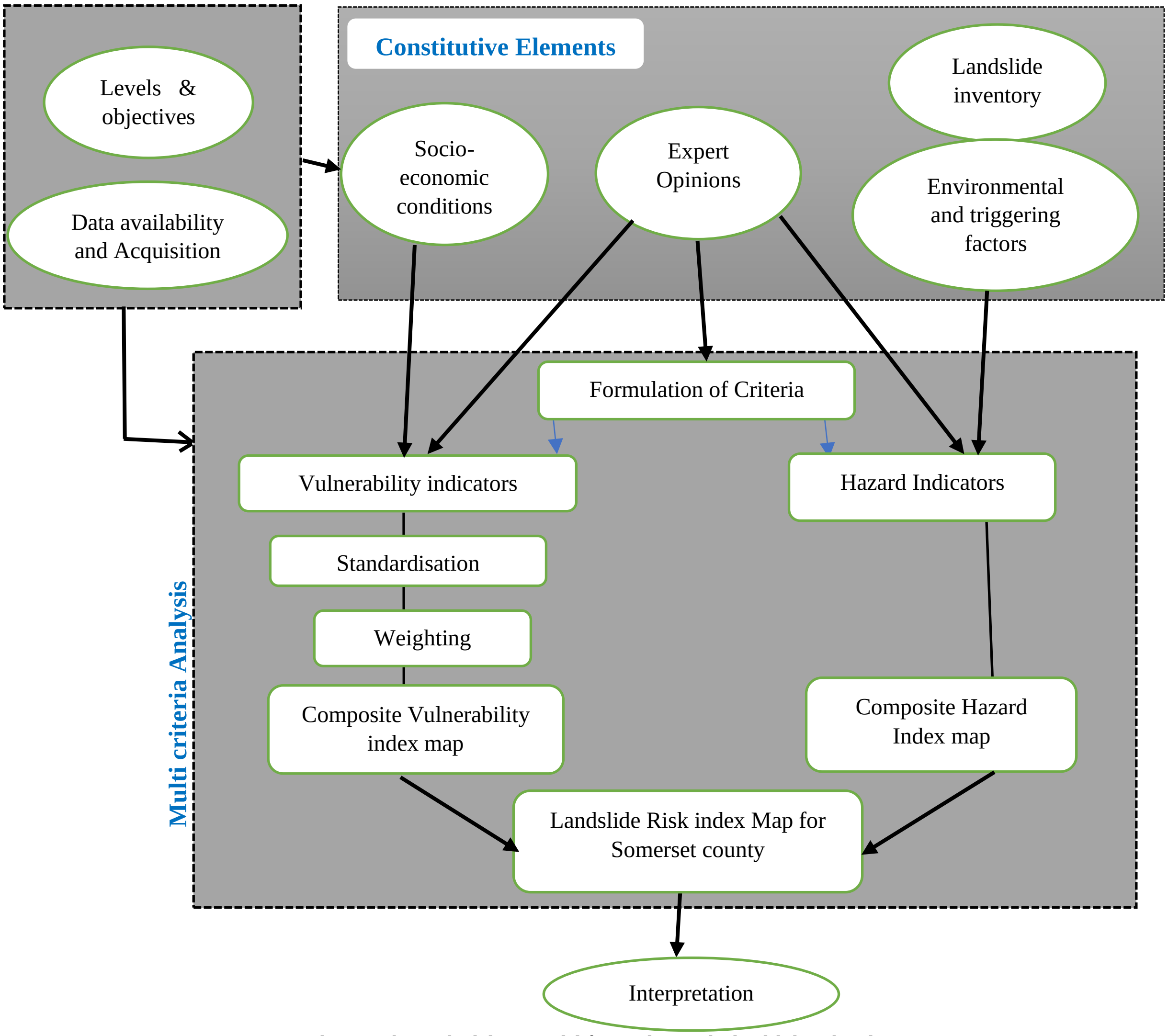

Figure 2. Showing the methodology model for producing the landslide risk index map.

4 Indicator analysis

4.1 Hazard indicators

Landslide hazard describes the probability of landslide activity at a given local, national or regional level. Each level may require a different method depending on the available data for the study area as well as the factors that are required to do the hazard assessment. The factors can be divided into two groups; the first group consists of condition factors that describe the properties of landslide location such as; slope, lithology, and aspect. The second group contains triggering factors that could lead to slope failure such as; rainfall and earthquake.

The hazard factors (indicators) were not ranked or weighted since a hazard index map was obtained from GeoSure dataset which is the national scale Natural Ground Stability developed by the BGS to provide information about different natural ground stability hazard that happens in the United Kingdom. One of the ground hazards described in the GeoSure database is landslides. The indicators that were used to estimate the landslide hazard level were the lithology, slope and water level in the rocks by the rainfall event. The probability of landslide occurrence in a specific class of lithology increased with increasing slope gradient. Also, the hazard rating increased with the amount of water soaked in the rocks during the winter season. The result of the hazard classification is represented by six classes described using letters from A to E (A = No hazard, E = High hazard) (Figure 3).

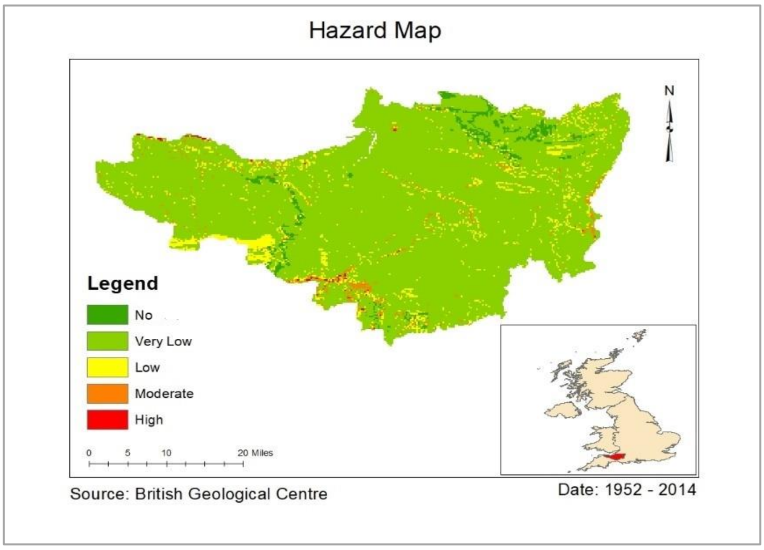

Figure 3. Showing the Landslide Hazard index map.

In order to determine the extent of the area that may be affected by the landslide hazard, descriptive statistics were done to identify the frequency of each classification level used in the landslide hazard index map (table 3). The probability of landslide occurrence in most areas in Somerset county is very low and a very small percentage of the area has a high probability of landslide occurrence. But that does not reflect the real impact of landslides in case a disaster happens because the effect of landslide may be bigger if it happens in a low hazard index area than a high hazard index area due to existing people affected or other vulnerability factors. Therefore, it is not good to use just landslide hazard maps and rely on them to create risk reduction plans, it is important to include different vulnerability indicators to create the risk index map and not just using landslide susceptibility maps or hazard maps only.

Table 3. Descriptive statistics of hazard index.

Hazard Index	Frequency	Percentage
No risk	894	3%
Very low	30238	88%
Low	2208	6%
Moderate	644	2%
High	78	1%

4.2 Vulnerability indicators

After reviewing several literature, different vulnerability indicators were found to be classified into social, economic, physical and environmental vulnerabilities. Physical vulnerability focuses on buildings location, water pipes, electricity pipes, roads and more. While social vulnerability focuses on number of people, the family structure, illiteracy because of lack of education, personal safety level and special needs among the people, for example; if the percentage of old people is high in the affected area it will indicate a high vulnerability posing a big challenge to deal with it. Economic vulnerability focuses on poverty, economic activities in the area. Environmental vulnerability focuses on land cover and soil type and how it may be affected by the landslide. In this study, because of the lack of data, only four factors were used as vulnerability indicators: buildings and transportation (physical vulnerability), population (social vulnerability) and green areas (environmental vulnerability). The indicator indices are computed by following methods used in other related studies such as (Abella et al., 2007) and other studies done for different hazard mapping.

4.2.1 Buildings indicator

The building indicator is one of the biggest elements that can be highly affected by mass movement since there is a positive correlation between the buildings and the population. Data about the number of buildings for each parish was available and the building index was developed using the following equation:

Building Index = (Number of buildings in the parish) / (Total number of buildings in the county)

The indexes near to 1 represented high vulnerability to the landslide. Standardization of the values was done using the minimum-maximum method, in which the parishes with a low value of index are less vulnerable than parishes with higher values (Figure 4).

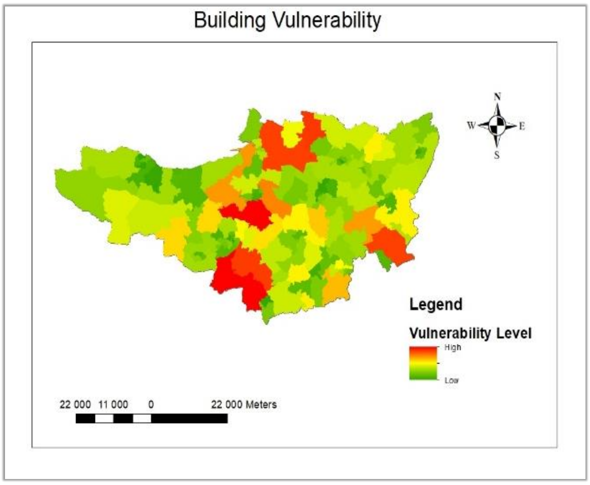

Figure 4. Buildings vulnerability.

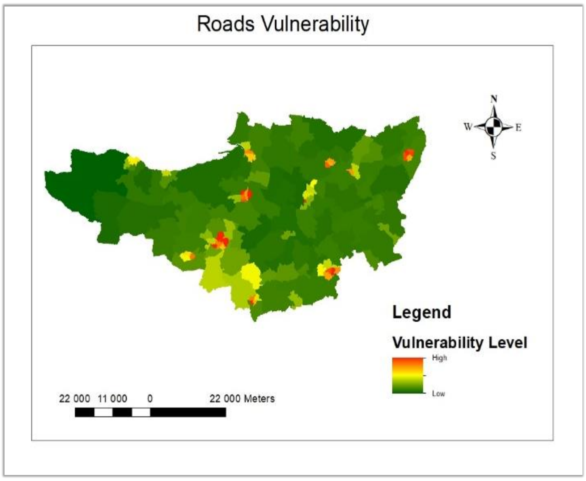

Figure 5. Roads vulnerability.

4.2.2 Transportation Indicator

The transportation system data in Somerset county was obtained from the UK ordinary survey. The density of the roads per square kilometer (km / km^2) was used as the indicator. All types of streets, roads, and railways were used in the calculation of the density. As expected, the highest number of parishes have a low index value and that means that they are all less vulnerable to the landslides because the transportation system has a few kilometers of roads and railways. The index values were standardized using the minimum-maximum method Figure (5) above.

4.2.3 Green Areas

The green area represented by the farms and parks in the county was used as an indicator of environmental vulnerability. The data about the green areas was obtained from the UK ordinary survey. The green areas distributed in the county, the density of green area per Km^2 was calculated by dividing the area of the green area by the total county area. The results were standardized using the minimum-maximum method (Figure 6) below.

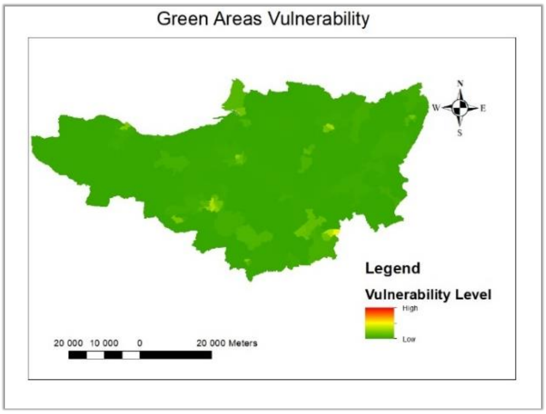

Figure 6: Green area vulnerability.

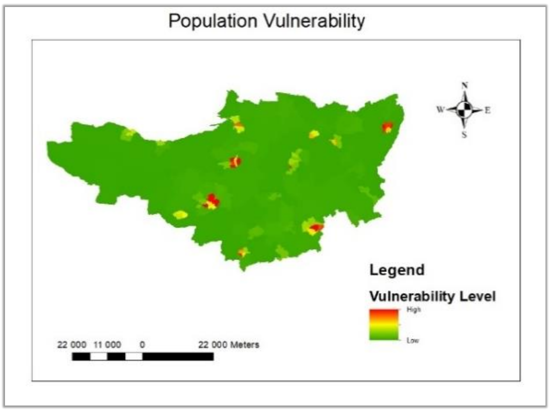

Figure 7: Population vulnerability

4.2.4 Population Vulnerability

For social vulnerability, the population density is used as the main indicator. The total number of people in Somerset county was 528137 people in 2011 depending on UK data service census support. The highest population density was 5922.37 persons per km^2 in the Taunton Eastgate parish. The parishes with low values of population density were associated with low vulnerability level, otherwise, the highest values of population density indicated a high level of vulnerability. The standardized map (figure 7) above was created after standardized the values of density using the minimum-maximum method.

5 Results and discussion

Using the weighted results in table 1 obtained from the rank order centroid method, the four indicator maps in Figures 4 to 7 including the weighted scores from table 1 were combined in GIS to construct the weighted map which gives the representation of vulnerability index for the study area. Achieving this was after deciding on the indicators and standardization as well as the determination of indicator weights, the analysis was carried out in ArcGIS software to obtain the vulnerability composite index map.

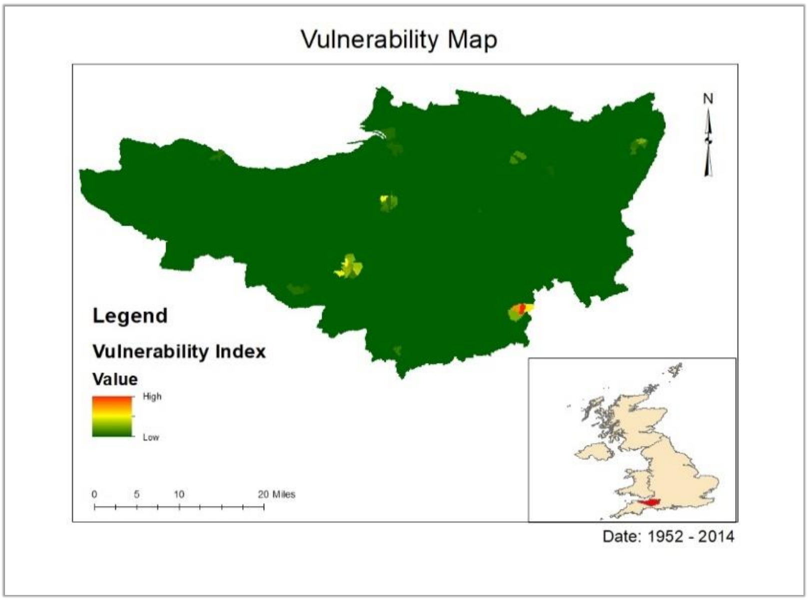

Figure 8. Showing the Landslide vulnerability index map.

In consideration of the indicators considered under vulnerability; Population, buildings and road networks are the most vulnerable to landslide hazards. As seen in figure 4, the buildings are more exposed to landslide occurrence which consequently indicates that the population is too vulnerable. However, the composite vulnerable map depicts that most areas are safe from damage that may be caused by the landslides. Overall it can be seen that the larger part of the county is less vulnerable to landslides with few instances having medium and high vulnerability index.

Cross analysis of the Hazard map (figure 3) and vulnerability map (figure 8) gives an indication that the probability of landslide occurrence is expected in more areas having a low vulnerability. Even places seen to have high chances of hazard occurrence are seen having low vulnerability levels indicating that landslides are expected to take place in areas with not so much social-economic activity going on. This is giving an indication of the levels of risk expected in the study area as we will see in the final risk index map

5.1 The final Landslide risk index Map

The Landslide risk index map was created by multiplying vulnerability index with hazard index (Figure 9). The risk index map shows the potential adverse consequences associated with landslide occurrence in Somerset county. The areas at risk can be dynamic depending on the prevailing development levels or economic activity taking place. The landslide risk increases mainly due to increased exposure of earth elements (vulnerability indicators) under threat. The landslide risk index map is a spatial integration of possible hazard coverage and level of vulnerability. The vulnerability map and hazard map are effectively combined to give an overview of landslide risk present in Somerset county.

This study used a semi-quantitative method to give an initial impression about the landslide risk and describe the risk scale, therefore the risk is divided into three levels namely high risk, medium risk, and low risk. The medium risk and low risk are required to be considered in the reduction plan while the high risk requires priority actions, response and mitigation to quickly reduce the risk.

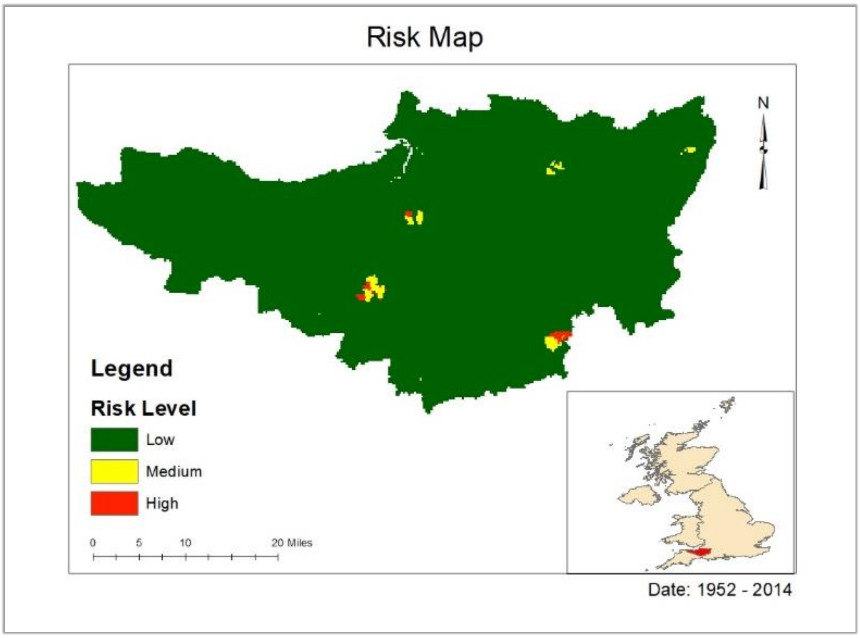

Figure 9. Landslide Risk index map for Somerset County.

Descriptive statistics for the risk index were used to check the extent of landslide impact; 99% of the county is at low risk to be affected by the landslides, the impact or the risk of the landslides will be low in most of the area. Otherwise, a small area of less than 1% of the total area will be affected by the landslides at high or moderate levels (table 4). It is obvious that the safe area increased in the risk index analysis (figure 9) when compared with the results from the hazard index analysis(figure 3), that means that the probability of landslide occurrence is not the only indicator for risk because maybe it will happen far away from the vital areas that contain people, buildings, and infrastructures and causing real damage. The descriptive statistics were obtained as a result of determining the number of pixels classified as the risk levels in ArcGIS;

Table 4. Descriptive statistics of risk index.

Risk Index	Frequency	Percentage
Low	33752	99%
Medium	218	0.5%
High	92	0.5%

landslide risk index descriptive statistics provided for the parishes is crucial for ranking them in order of importance for landslide risk reduction efforts and measures. The landslide risk mapping method used here facilitates the evaluation of the indicators responsible for high-risk index values in the areas having high-risk levels. Local authorities and other environmental planners can easily observe landslide occurrence as the landslide risk map acts as a warning tool for the allocation of mitigation measures and other focused studies.

High Landslide Risk Areas; The high risk obtained for the study area is only 0.5%. High landslide risk areas can be seen in parishes that according to the vulnerable index map (figure 8) and the hazard index map (figure 9) had high index values. Breaking down to further analysis, it is realized that these parishes have high levels of population density which proportionally indicates that the building index and the road index are high in those parishes and thus contributing to the high-risk level. The hazard index map indicated a relatively low -moderate probability of landslide occurrence in those areas and looking at the landslide inventory map (figure 1), some of the areas having high landslide risk have in the past experienced landslides. This is an indication that people have been affected in those areas and that landslide can still happen at any time thus more efforts to mitigating the disasters are required.

Moderate Landslide Risk Areas; The medium risk obtained for the study area is 0.5%. Moderate landslide risk areas can be seen surrounding most of the areas mapped as high landslide risk areas. These areas are a crosscut between moderate hazard index and vulnerable index values, in other words, they possessed an average probability of landslide occurrence as well as average consequence situations. Also, analysis of the landslide inventory map (figure 1) shows that some areas having moderate landslide risk have in the past experienced some landslides. In as much as the risk is medium, efforts can be accorded to incorporating them in the landslide disaster management plan to be aware of any damage that may happen.

Low Landslide Risk Areas; The low risk obtained for the study is 99%. Most of the study area can be seen at low risk from the landslide occurrence. The areas that are seen to have experienced landslide events in the landslides inventory map (figure 1) are seen as having low risk in the risk map (figure 9). However, in the Hazard Map (figure 3), it is seen that the probability of landslide occurrence is high in 1% and moderate in 2% of the study area, meaning that in as much as the probability of landslide occurrence is high, the risk is low; that is to say that the population or other social-economic aspects may not be seriously impacted by the occurrence of the landslides. Likewise, the areas having low risk can be incorporated in any reduction plan in order to comprehensively analyze landslide disaster.

Combining the risk map with the administrative boundaries map to analyze the risk at parish level shows that; six parishes have more than 90% of high risk namely Bridgwater Victoria, Taunton Fairwater, Yeovil Central, Yeovil West, Comeytrowe and Yeovil East. There are 15 parishes with medium risk, divided into two groups. The first group contains parishes that have more than 90% of their area considered as a medium, the second group has less than 60% from their area considered as medium risk and the rest of the area considered as low risk (table 5).

Table 5: Overview of medium risk in 15 parches

Group 1 - medium risk[a]	Group 2 - medium risk[b]
Taunton Eastgate	Chard Holyrood
Bridgwater Fairfax	Frome Market
Bridgwater Dunwear	Bridgwater Westover
Taunton Pyrland and Rowbarton	
Taunton Blackbrook and Holway	
Taunton Halcon	
Taunton Lyngford	
Bridgwater Westover	
Frome College	
Wells St Cuthbert's	
Yeovil South	
Taunton Manor and Wilton	

a More than 90% of the area considered medium risk.
b less than 60% of the area considered medium risk

6 Conclusion

Applying multi-criteria decision Analysis MCDA integrated with GIS to create a landslide risk map needs a better understanding of the indicators, structuring of the indicators and how to distribute the uncertainty. The semi-quantitative risk assessment used in this study does not require accurate numerical data, but it requires the right hierarchy of risk factors reflecting the rank against qualification. Landslide risk depends on a combination of elements that comprise both hazard and vulnerability and landslide risk mapping underlines the combination of both natural and human factors that could create landslide risks. The consideration of vulnerability factors in risk assessment mapping is very useful because it gives an understanding of the driving forces and distinct impacts of possible landslide disaster. Both the hazard (susceptibility) map and vulnerability map contribute to conclusive landslide risk analysis; the vulnerability map literally improves on assessing where people are more vulnerable than others while the hazard map will enhance the prior identification of landslide occurrence. This greatly supports various local authorities and environmental agencies in performing informed based decision-making regarding landslide disaster management. The approach of integrating data from hazard and vulnerability into a risk analysis as presented in this study facilitates the identification and categorization of landslide risks at a reasonable scale. Somerset county can be considered as a more safe area from landslide occurrence since most of the area is considered as low-risk area, also the probability of landslides occurrence is low and the high vulnerability areas are so small to consider them as strongly threatened. Thus far, not many studies discuss the landslide risk mapping assessment, and most of the works focus on Landslide Susceptibility Mapping (LSM) and reclassification and release these maps into different administration levels without taking into consideration the different vulnerability indicators.

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