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Article

Development of Site-Specific Wind Hazard Map for Peninsular Malaysia via Spatial Modeling

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Abstract: The commonly used approach to predict and evaluate the wind risk in Peninsular Malaysia is to employ the basic wind speed (V_s) hazard map, which underestimates the real damage due to the limitation of factors considered by the current map. This paper aimed to develop a new wind hazard map for Peninsular Malaysia based on the site wind speed (V_{site}) rather than the V_s using the Geographical Information System. The development of the V_{site} map considered the effects of the Land Use Land Cover (LULC) and the topography conditions that were not taken into consideration by the Malaysian Standard during the development of the V_s map. The statistical analysis proved that the wind hazard in Peninsular Malaysia is directly proportional to the LULC and inversely proportional to the Hill Shape Multiplier. In addition, the results showed that the existing V_s map underrated the wind hazard in Peninsular Malaysia by almost 9.02% to 17.79% compared to the developed V_{site} map. Therefore, the use of the newly developed map to evaluate the wind hazards will significantly enhance the assessment, and the new map has the potential to be incorporated into the Malaysian Standard for this purpose.

Keywords: wind hazard maps; geographical information system; terrain height multipliers; hill shape multipliers

1. Introduction

Wind may cause severe damage to property, loss of life, and other catastrophic events. According to Tamura and Cao [1], severe winds were the main cause of death in the previous decade compared to other natural disastrous events. Thus, it is essential to fully understand what factors alleviate the windstorm frequency and intensity so that effective risk management methods can be established [2]. Paton [3] suggested that reconsidering the basic assumptions of the existing disaster risk methods should be an urgent matter, especially with the recent advances in the techniques of measurement and analysis. This requires wind engineering experts from all over the world to join their forces and produce effective measurements to help minimize the wind-related hazards [1].

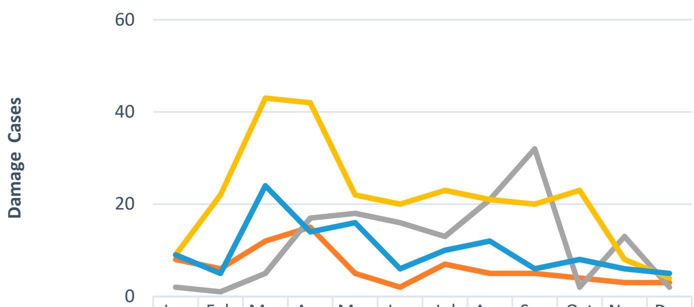
Malaysia is an Asian country located near the equator and is well-known for its rainforests. This makes it extremely important to investigate its wind flow pattern, which is mainly controlled by two major monsoon periods, namely the northeast monsoon (November to March) and the southwest monsoon (May to September) [4]. A specific period between the two major monsoons (April and October) is called the intermonsoon, in which frequent thunderstorm events occur, causing stronger and gustier windstorms than those of the northeast and southwest monsoons. These windstorms are classified within the meteorological disaster subgroup [5].

The International Disaster Database (EM-DAT) [6] classified windstorms in 2004 as one of the top 10 natural events in Malaysia. Windstorms killed 270 individuals in the state of Sabah on 26 December 1996, and were responsible for the suffering of more than 40,000 people on the East Coast of Peninsular Malaysia on 6 November 2004. Windstorm events have always been on the Malaysian news, and Table 1 presents the disasters and casualties caused by windstorms in Malaysia between 1960 and 2005 as reported by EM-DAT [6]. EM-DAT [6] also reported that seven major catastrophic events caused by windstorms occurred between 1960 and 2016: Two tropical cyclones, a convection storm, and four other storm types. In addition, Bachok et al. [7] stated that windstorm occurrences in Malaysia between 2000 and 2012 occurred in 681 different locations and resulted in a financial loss that exceeded 1M USD.

Table 1. Windstorm Disaster in Malaysia between 1960–2005 [6].

Start Date	End Date	Location	Disaster Subtype	Total Death	Total Affected	Associated Disaster
07/01/1968	07/1/1968	Johor	Nil	21	10,000	-
26/12/1996	28/12/1996	Sabah	Tropical Cyclone	270	4176	Flood
23/8/1997	27/8/1997	Kedah, Perlis, Penang	Tropical Cyclone	2	2115	Flood
23/8/1997	27/8/1997	Kedah, Perlis, Penang	Tropical Cyclone	2	2115	Flood
27/9/2000	27/9/2000	Penang	Nil	-	500	Nil
30/3/2002	30/3/2002	Klang	Convective Storm	2	155	-
16/7/2004	16/7/2004	Kedah State	Nil	-	1000	Nil
06/11/2004	06/11/2004	Kuala Lumpur	Nil	1	40,000	Flood, Land Slide, Mud

The consideration of all design factors plays a vital role in efficiently mitigating the damage of windstorm [7–9]. Wan Chik et al. [8] investigated the damage of windstorms in Malaysia between 2007 and 2012 based on location. They found that most of the damage occurred in the Northern Region of Peninsular Malaysia and at definite locations. They also concluded that the severity of the windstorm damage increased from one year to another, which was also supported by Majid et al. [9]. Majid et al. [9] found that the windstorm in 2010 killed 3 people, injured 30, and destroyed 1012 houses (roofs) in Peninsular Malaysia. Figure 1 depicts the damage cases reported by Bachok et al. [7] throughout the country between 2000 and 2012, employing both location and date. It is noticed that the highest number of windstorms in Northern, Southern, and Central Regions took place between March and April, which is the transition period between the two monsoons. However, the windstorms in the East Coast Region peaked between August to September. Hence, the study showed that windstorms in Malaysia happen all the year. However, they are most frequent during the transition of the monsoon season.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Central	8	6	12	15	5	2	7	5	5	4	3	3
East Coast	2	1	5	17	18	16	13	21	32	2	13	2
Northern	9	22	43	42	22	20	23	21	20	23	8	4
Southern	9	5	24	14	16	6	10	12	6	8	6	5

Figure 1. Windstorm occurrence based on location and date between 2000 and 2012 in Peninsular Malaysia.

In the field of wind engineering, the wind risk for any specific site is usually indicated based on the potential wind speed at that site. A few wind hazard maps have been constructed utilizing the basic wind speed (V_s) to determine the wind load exerted on a structure before the consideration of other factors, like the altitude and the effects of the topographic and aerodynamic shape factors. The drawback of these maps is that they are assessed using the probabilistic method of the past recorded wind speed data, which may lead to the underestimation of the wind speed risk due to the incompetent interpretation of the real potential of wind speed. For example, the Terrain Height Multiplier ($M_{z,cat}$) related to the condition of the Land Use Land Cover (LULC), as well as the Hill Shape Multiplier (M_h) of the topographical condition, may increase. The Malaysian Standard (MS1553:2002) [10] divides V_s of Peninsular Malaysia into two main zones on the map. However, the accuracy of estimating the potential risk is questionable, since the map interpolation does not rely on a spatial analysis technique.

As mentioned earlier, V_s is denoted as potential of wind speed for a specific location without considering the effect of the geographical factors. However, the potential of wind speed is more realistic when the geographical factors are considered because the wind changes its speed characteristics based on the nature of the terrain. Thus, the wind speed that considers the effects of both LULC and the topographical conditions is called site wind speed (V_{site}). The MS1553:2002 [10] employs V_{site} at some specific locations by multiplying V_s with $M_{z,cat}$ and M_h. However, to determine V_s in places other than the specific locations, the nearest station must be referred to. Like the previous method, this method is highly prone to inaccuracy in the evaluation of the risk.

Therefore, this study aimed to construct a wind hazard map for areas of Peninsular Malaysia that are not considered as a reference in the MS1553:2002 [10] by considering the V_{site} data (LULC and topographic condition) to provide reliable information regarding the wind potential risk at these locations. The potential of wind hazard was uniquely established via spatial analysis techniques. Thus far, a few studies [11,12] developed wind hazard maps based on V_{site} data. However, their maps were not validated with any existing studies. For this reason, the constructed hazard map in this study will be verified with past recorded damages.

2. Research Methodology

2.1. The Location of the Study

The selected location for this study was Peninsular Malaysia (Figure 2), with a total area of 130,590 km^2, which is still within the hazard assessment range of recommended sizes by Van Westen [13]. For the sake of this study, Peninsular Malaysia was divided into four regions:

1. Northern Region: Perlis, Kedah, Pulau Pinang, Perak
2. East Coast Region: Kelantan, Terengganu, Pahang
3. Central Region: Selangor, Kuala Lumpur
4. Southern Region: Negeri Sembilan, Melaka, Johor

2.2. The Wind Hazard Map Development

The construction of the wind hazard map involved several stages, as explained in this section.

2.2.1. Basic Wind Speed Map

The first phase of the study commenced by adopting a qualitative approach to gather data from the existing recorded windstorm damages. After all the data was collected, the wind hazard map using the site wind speed (V_{site}) was produced. V_{site} was calculated using the following Equation:

$$V_{site} = V_s \cdot M_{z,cat} \cdot M_h \quad (1)$$

The basic wind speed data employed in the current study were provided by the Malaysian Meteorological Department (MMD) Station as presented in Table 2. All the provided wind speed data was measured at a height of 10 m for a 50-year return period. It is worth mentioning that the 50-year return period was adopted throughout the whole study. According to Sundaraj [14] and Mornet et al. [15], the value of the basic wind speed is significantly affected by the length of the historical wind speed data, and the longer the period, the better the assessment. Furthermore, the height of 10 m is the standardized reference height all over the world [16]. The average time of the gust wind speed measurement by the MMD is three seconds. It is worth mentioning that the basic wind speed (V_s) data was provided by the MMD from 20 different stations. The wind hazard map was developed using the Geographic Information Systems (GIS), which has the capability to interpolate the wind speed data via various statistical methods. The study also employed spatial interpolation methods for the prediction of V_s at the investigated locations, and the spatial interpolation was generated using the Inverse Distance Weighting (IDW) techniques as used by previous studies [17–19]. The IDW method calculates the assigned values to the unknown points with the weighted average of the values available at the known points. The weighed value is basically the inverse of the distance raised to a power. The general form of finding an interpolated value at a given point using IDW is presented in Equation (2):

$$z_u = \frac{\sum_{i=1}^{s} z_i {d_{iu}}^{-k}}{\sum_{i=1}^{s} {d_{iu}}^{-k}} \tag{2}$$

where z_u is the unknown value of estimated at u, z_i is the attributed value at control point i, d_{iu} is the distance between points i and u, s is the number of control points used in estimating, and k is a factor.

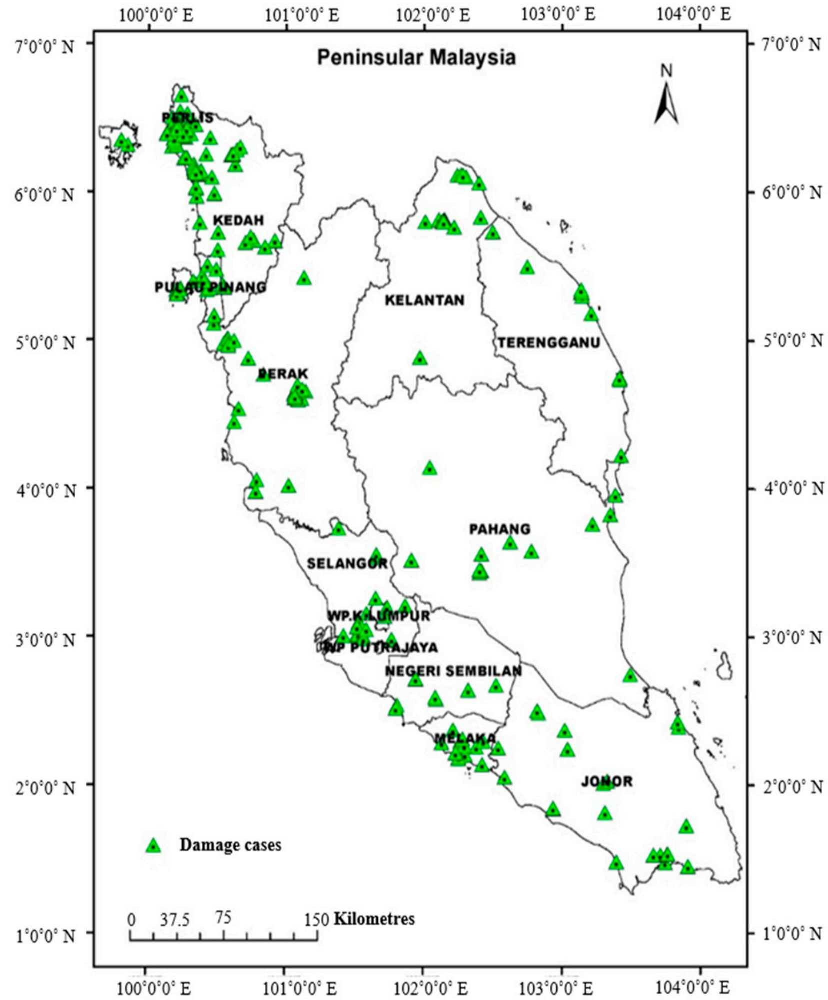


Figure 2. Selected area of study.

Table 2. The 50-year return period basic wind speed in Peninsular Malaysia.

No	Station	50-year Return Period Wind Speed (m/s)	Period	No	Station	50-year Return Period Wind Speed (m/s)	Period
1	Chuping	25	1972–2012	11	Melaka	28.5	1941–2012
2	Alor Setar	29.2	1939–2012	12	Kluang	31.3	1974–2012
3	Butterworth	24.5	1985–2012	13	Senai	29.1	1974–2012
4	Bayan Lepas	27.2	1985–2012	14	Mersing	31.6	1939–2012
5	Ipoh	30.8	1939–2012	15	Muadzam Shah	24.4	1983–2012
6	Sitiawan	25.3	1939–2012	16	Temerloh	27	1978–2012
7	Batu Embun	26.8	1983–2012	17	Kuantan	30	1950–2012
8	Cameron Highlands	28.7	1983–2012	18	Kuala Terengganu	29.8	1978–2012
9	Subang	31	1966–2012	19	Kota Bahru	32.4	1939–2012
10	Petaling Jaya	31	1971–2012	20	Kuala Krai	27.6	1985–2012

2.2.2. Terrain Height Multiplier Mapping

To map the area terrain, the LULC map data was used as input and categorized based on the terrain category. In order to estimate M_h, a terrain classification map was developed based on the obstructions of the terrain as stated in MS 1553:2002 [10]. The $M_{z,cat}$ coefficient map was generated from the reclassification of the LULC to the weighted scale, which relies on the coefficient factors.

2.2.3. Topographic Wind Multipliers

The Hill Shape Multiplier (M_h) was obtained based on the slope category in accordance with MS 1553:2000 [10]. The slope category of the area was generated using the Digital Elevation Models (DEM) data, as well as the Shuttle Radar Topography Mission (SRTM) data. The slope category was generated in accordance to Table 3.

Table 3. Hill shape Multiplier (M_h).

Category	Degree	Upwind Slope	M_h
1	<2.9%	<0.05	1.00
2	2.9	0.05	1.08
3	5.7	0.1	1.16
4	11.3	0.2	1.33
5	16.7	0.3	1.49
6	≥24.2	0.44	1.71

2.3. *Wind Hazard Maps Validation*

To validate and evaluate the performance of the four developed wind hazard maps, both past damage and statistical analysis were used. The first map was developed based on V_s, the second was based on V_{site}, and the remaining maps (third and fourth) were based on the average V_{site} value according to district and subdistrict. The main purpose of adopting the statistical analysis as a verification method was to compare the performance of V_s and V_{site} maps. Histogram analysis, skewness analysis, and Cumulative Distribution Function (CDF) were chosen to assess the frequency and probability of the damages based on their level of hazard. It should be noted that, in this study the wind hazard was defined as the wind speed value, which was also used by Rose et al. [20] to evaluate wind turbine performance against hurricane hazard.

2.3.1. Histogram Analysis

The histogram was first introduced in 1895 by Karl Pearson, and it is an accurate representation of the distribution of the numerical data. It can give a rough estimation of the density of a continuous variable and can be thought of as a kernel density estimation, since it uses a kernel to yield a smoother probability density function, which precisely reflects the distribution of the underlying variable. The histogram is defined as

$$n = \sum_{i=1}^{k} m_i \quad (3)$$

where n is the number of observations, k is the total number of bins, and m_i is the histogram value.

In a more general mathematical form, it can be said that a histogram is a function "m_i", which counts the number of observations that falls into each of the separate bins, while the graph of a histogram is merely one way to represent a histogram. Moreover, a cumulative histogram counts the cumulative cases over the range of cases. Equation (4) defines the histogram in a mathematical function.

$$M_i = \sum_{j=1}^{i} m_i \quad (4)$$

where M_i is the cumulative histogram and m_i is the histogram value. A cumulative histogram is a plot that counts the cumulative number of observations in all the bins up to the specified bin. This is the basis of producing CDF.

2.3.2. Skewness Analysis

The skewness analysis was performed to view the tendency of the wind speed value against the location of damage. Skewness is a symmetry measure, and it was calculated as follows:

$$skewness = \ ((\mu - Mo))/\sigma \quad (5)$$

where μ is the mean, Mo is the mode, and σ is the standard deviation. For a normal distribution, the skewness is always zero. However, the non-normal distribution skewness could be positive or negative.

2.3.3. Cumulative Distribution Function

The cumulative distribution function (CDF) is a function that provides the probability associated with a function, and it is suitable for comparisons of multiple datasets. It was employed in this study to visualize the performance of the developed wind hazard maps and to display the probability value for a specific target or return value. The cumulative distribution function is defined as the integral of its probability density function f_X:

$$F_X(x) = \int_{-\infty}^{x} f_X\ (u) du \quad (6)$$

3. Results

3.1. Windstorm Database

All the archived wind damages and trends data from 2009 until 2016 were examined and analyzed according to the geographical location, date, and time. A total of 289 windstorm cases occurred during this period were assigned to the place of occurrence as depicted in Figure 3.

Figure 3 shows that the Northern Region of Peninsular Malaysia experienced the highest windstorm damage during the recorded period with a total of 159 cases followed by the Eastern Region (60 cases), whereas the Central Region had the lowest damage with only 20 cases. The Southern Region registered 50 cases in the three states, with Johor the leading state with 28 cases. The Northern and Central Regions windstorms caused destruction of houses and vehicles, roofs and trees uplifting, power failure, and human casualties, while the Eastern and Southern Regions experienced house and vehicle damaging, lifting of roofs and trees, animal loss, and human injuries. Despite the similarities in the type of damages in the four regions, the Eastern and Southern Regions did not experience any human loss. Most of the recorded damage cases were associated with floods.

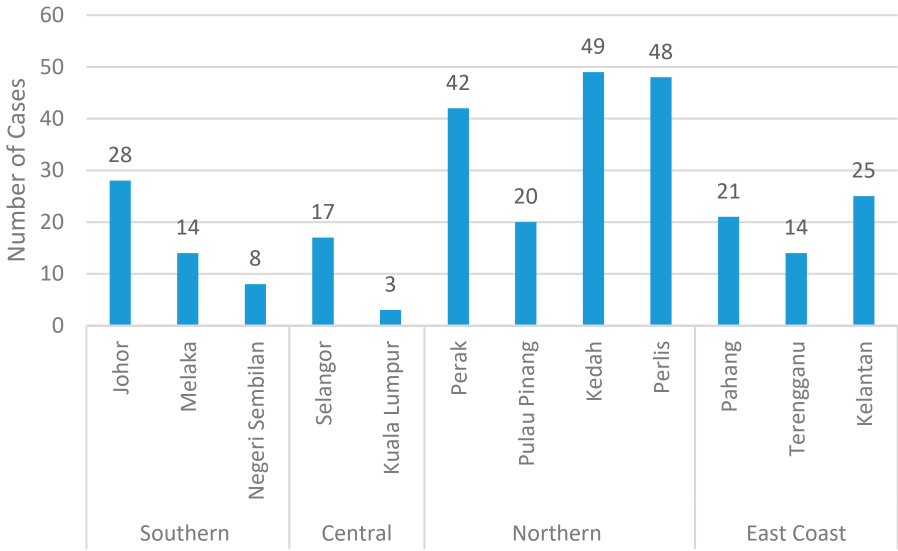


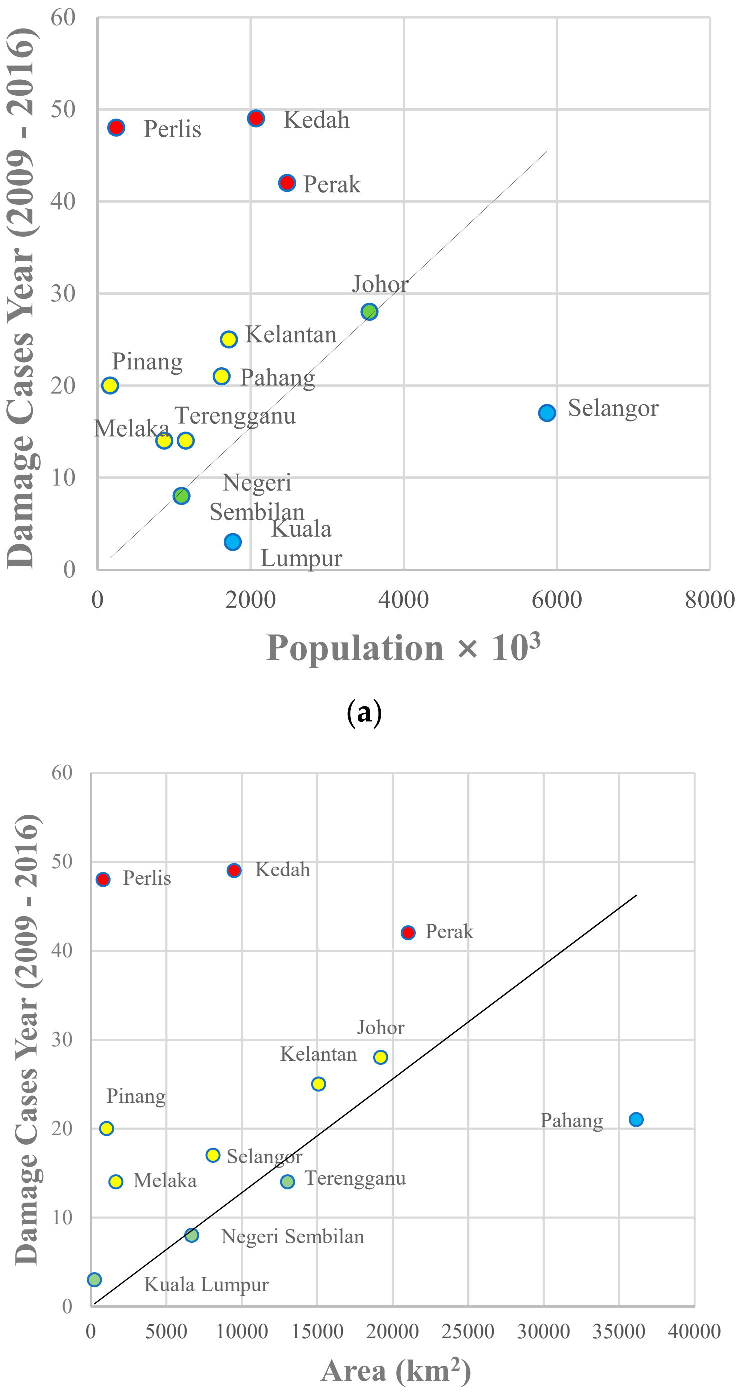
Figure 3. Windstorm damage cases from 2009 to 2016.

It is obvious that the windstorm events were scattered all over Peninsular Malaysia, and the Northern Region was the most affected. The most developed state (Kuala Lumpur), which falls into terrain category 4, experienced the lowest number of windstorms during the recorded period due to its high surface roughness factor. On the contrary, Kedah, Perlis, and Perak were severely struck by windstorms. These states are considered the least developed in Malaysia and are classified as terrain category 1 (flat and open surface). The same observations were reported by Wan chik et al. [8], who found that Kedah suffered more windstorm damage due to the effect of the terrain category and due to being less developed.

It is well-known that in addition to the hazard exposure and vulnerability, damage is a function of the socioeconomic status. In this study, the social vulnerability indicators (demographic features) were taken into consideration. Using the database to investigate the relationship between the windstorm damage cases and the demographic condition (population and area) during 2009–2016, Figure 4 was constructed. According to the results in Figure 4, Kedah, Perlis, and Perak, which had the highest number of windstorms, were less populated than Selangor and smaller than Pahang in terms of area. From a natural point of view, there is a partial relationship between the population, area, and the windstorm damage, as it is expected that more populated areas are more prone to damage. However, the demographic conditions (population and area) may not always be an accurate indication of the windstorm damage. From an economic prospective, the economy of the Northern Region (Kedah, Perlis, and Perak) is weaker compared to that of the Central Region (Selangor and Kuala Lumpur), indicating that the more developed the city, the less severe the windstorm damage.

Validation of the Obtained Windstorm Database

Following the same technique of validation as previous researchers [21–23], the obtained windstorm database results were validated with the results of Bachok et al. [7], as shown in Figure 5. The results of both studies indicated that the frequency of windstorms (Figure 5a) peaked in both April and September (transition monsoons). The curve behavior of the current study shows a similar trend to that of Bachok et al. [7], even though they are not perfectly matched.



(**a**)

(**b**)

Figure 4. Relationship between windstorm damage and (**a**) population; (**b**) area.

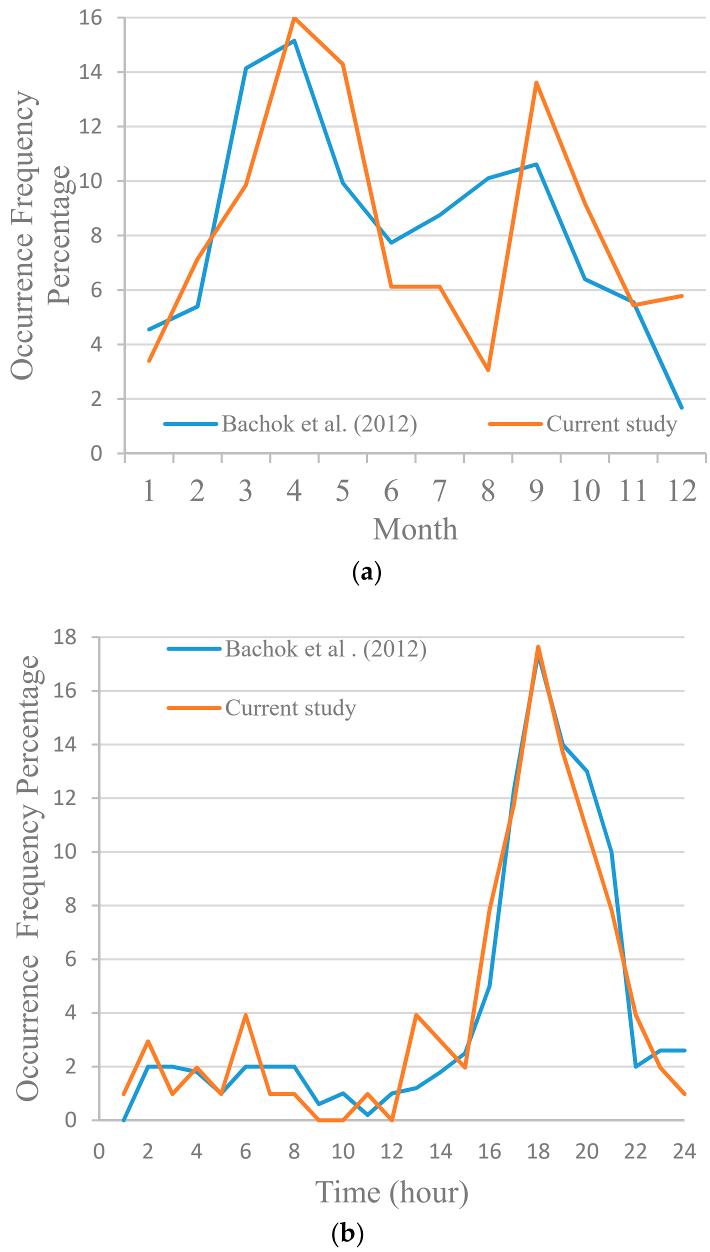


Figure 5. Validation of the occurrence frequency of windstorm damage cases according to (**a**) month; (**b**) hour.

The windstorm occurrence time was also compared, as shown in Figure 5b. The results showed perfect agreement, as the two curves almost overlapped each other, and the peak occurrence time was found to happen between 16:00 to 20:00. Therefore, the data obtained in this study could be employed to develop the wind hazard maps.

3.2. Geodatabase Data Classification

3.2.1. Land Use and Land Cover Data

The terrain category data representing the LULC for the studied locations were based on MS 1553:2002 [10]. However, since the categories in MS 1553:2002 [10] did not match the terrain of these locations, two new categories were introduced to match the Terrain Height Multiplier ($M_{z,cat}$) of these locations based on the study by Wieringa [24] as presented in Table 4. This approach was followed by Lin [25], who developed the $M_{z,cat}$ coefficient map.

Table 4. Coefficients and descriptions of the terrain categories.

Category	Description	$M_{z,\,cat}$
1	Exposed open terrain with few or no obstructions, e.g., open sea.	1.120
2	Water surfaces, grasslands with few well-scattered obstructions with a height generally from 1.5 m to 10 m.	1.060
3	Open Terrain: Mixed area between few well-scattered obstructions with a height generally from 1.5 m to 10 m, with terrain with numerous closely spaced obstructions from 3.0 m to 5.0 m.	1.000
4	Terrain with numerous closely spaced obstructions from 3.0-m to 5.0-m high, such as areas of suburban housing. Low crops.	0.9150
5	Terrain with numerous large, high (10.0 m to 30 m), and closely spaced obstructions, such as large city centers and well-developed industrial complexes. High crops. Scattered obstacles.	0.8300
6	Regular large and close obstacle coverage, such as deep forest areas.	0.7500

Figure 6 shows the different land use categories using the $M_{z,cat}$ coefficients in Table 4 to indicate the surface roughness. It is clearly noticed that a huge part of Peninsular Malaysia fell into categories 4, 5, and 6, signifying that these areas possessed a high surface roughness, which could obstruct the wind movement and lower the produced land use coefficient factors.

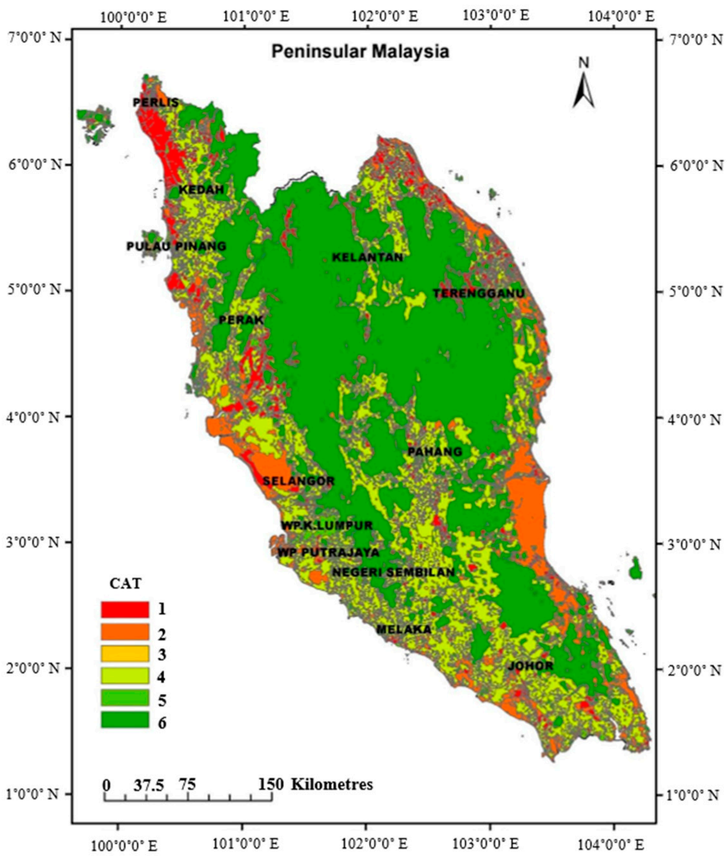


Figure 6. LULC based on the terrain category.

Figure 7 depicts the developed $M_{z,cat}$ coefficient map using the spatial interpolation method. The map can be easily used to determine the coefficient factor according to the terrain classification, as well as the wind speed increment or decrement. The map shows that the lowest coefficient factor was found in the interior regions of Peninsular Malaysia, where the terrain category was classified as deep forest area (category 6), while the exterior coastal regions had the highest coefficient factor (category 2) as a result of their low roughness coefficient. Thus, these coastal areas are more vulnerable to windstorms. However, there were some interior regions with high coefficient factors and some coastal areas with low coefficient factors.

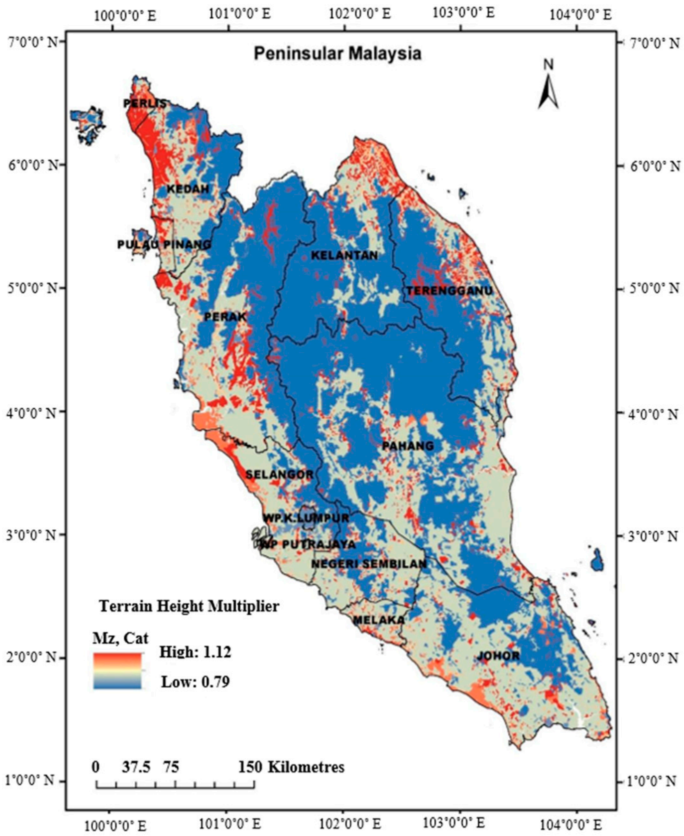


Figure 7. The Terrain Height Multiplier ($M_{z,cat}$) map for Peninsular Malaysia.

By comparing the number of damage cases based on the $M_{z,cat}$ coefficient, it can be noticed from Table 5 that 81.63% of the windstorms from 2009 to 2016 occurred in terrains with low $M_{z,cat}$ coefficients (1, 2, and 3) compared to 18.36% in terrains with high $M_{z,cat}$ (4, 5, and 6). Therefore, it can be generally said that the windstorm occurrence increased with the increase of the terrain category and the decrease of the $M_{z,cat}$ coefficient. In other words, the roughness of the location played a significant role in the occurrence of windstorms, as Lu et al. [26] and Tan and Fang [27] found in their studies. This also indicates that the population did not contribute as much to the damage severity as the terrain. The highly populated regions experienced less damage than the lesser populated ones. In addition, it is clear that the most developed regions were less affected by the windstorm events during the recorded period.

Table 5. Damage cases based on LULC category.

Terrain Category	Number of Cases	Percentage (%)
6	1	0.35
5	8	2.77
4	45	15.57
3	106	36
2	9	3.11
1	125	42.52

It can be seen that the percentage of category 2 (3.11%) was lower than the values of categories 1 and 3 because there were not many residential units within this type of terrain. In addition, the MS 1553:2002 [10] only has four main terrain categories, and it considers categories 1 and 2 mentioned in this study as one category. However, in this study, the four main terrain categories in MS 1553:2002 [10] were reclassified into six categories to help investigate each terrain as a single identity.

3.2.2. Data Hill Shape Multiplier

Ngo and Letchford [28] and Chamanehpour [29] mentioned that the wind speed increases as it passes across a hill or a cliff. Thus, the Hill Shape Multiplier (M_h) was taken into account in the current study. Figure 8 shows the M_h coefficient map constructed by employing the DEM and reclassifying the slope degree of the investigated terrains with respect to their coefficients. Figure 8 depicts the slope degree of the whole Peninsular, in which the slope of the interior areas is higher than the slope of the coastal regions due to the difference in the nature of the terrains. The interior regions are mountainous, while the coastal areas are mostly plain. The M_h coefficient and the distribution of the damage cases are presented in Table 6. It is clear that the occurrence of windstorms is inversely proportional to the slope degree of the terrain. Therefore, having a plainer area subjects the location to a high potential of having frequent windstorms. That is to say, the development of a particular location is a key factor to reduce the damage of windstorm events.

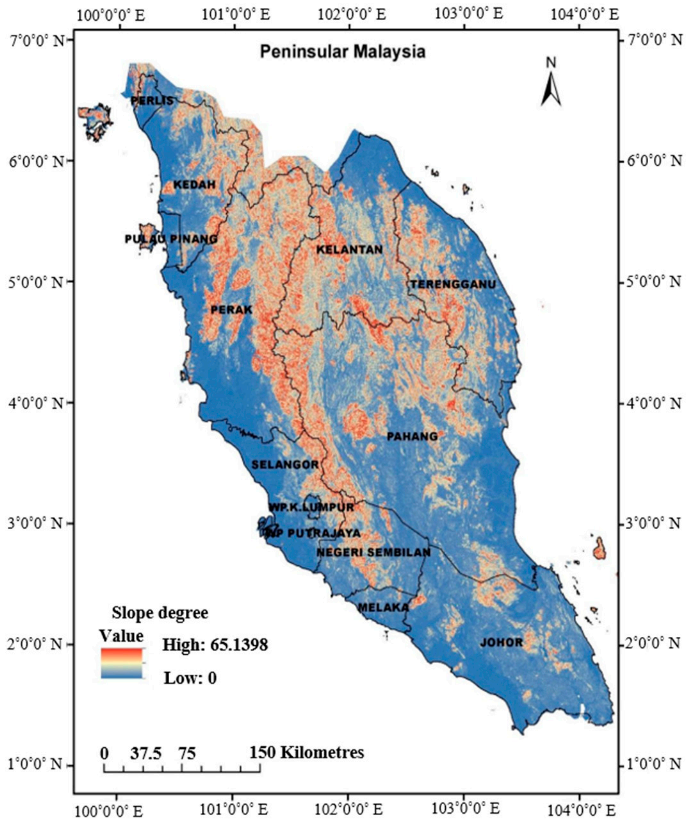


Figure 8. The slope degree for Peninsular Malaysia.

From Section 3.2, it can be concluded that the terrain conditions and the economic status of these terrains played a very crucial role in the occurrence of the windstorm damage from 2009 to 2016, while the social demographic features (population) was not a significant factor in the occurrence of windstorm damages in Peninsular Malaysia.

Table 6. Damage cases based on the slope conditions.

Category	Degree	M_h	Damage Cases	Percentage (%)
1	<2.9	1	264	89.8
2	2.9	1.08	22	7.48
3	5.7	1.16	6	2.04
4	11.3	1.33	2	0.68
5	16.7	1.49	0	0
6	>24.2	1.71	0	0

3.3. Development of Wind Hazard Map

The wind hazard map was developed by multiplying the basic wind speed (V_s) with the Terrain Height Multiplier ($M_{z,cat}$) and the Hill Shape Multiplier (M_h). The V_s map, shown in Figure 9, was constructed using the 50-year return period data in Table 2. The map shows that the V_s was generally higher at the Central and Southern Regions compared to the other regions in the Peninsular. The highest recorded wind speed was 32.5 m/s and the lowest was around 24 m/s.

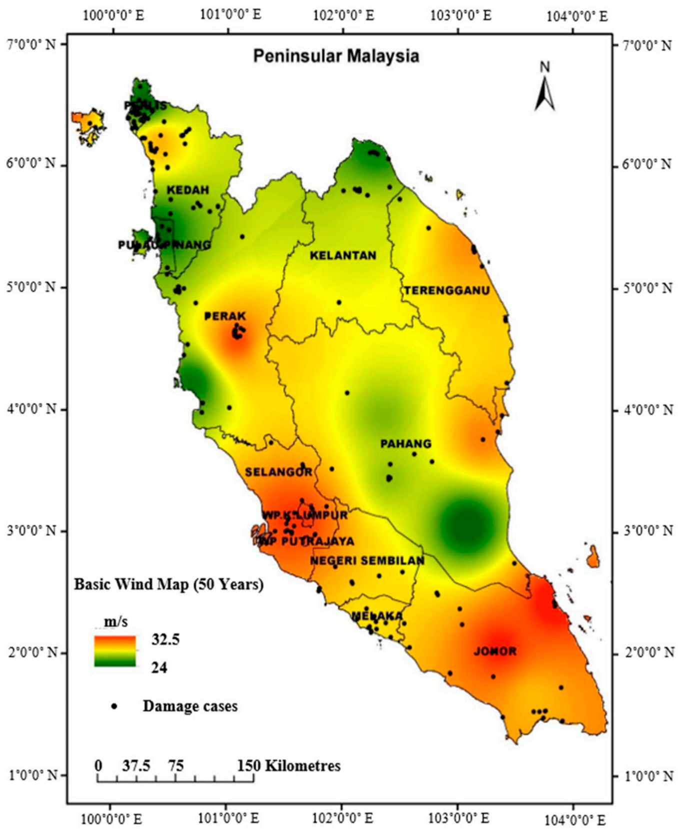


Figure 9. Basic wind speed (V_s) of Peninsular Malaysia.

Figure 10 depicts the established wind hazard map. By looking at the developed map, locations with a potential high wind speed can be easily identified. For instance, the highest wind speed in the Northern Region was observed in Perak (Lembah Kinta), Kedah, and Perlis, which agreed well with the findings of previous researchers [8,30,31]. For the East Coast Region, both Kuala Terengganu and Marang were found to have the highest wind speed, while Senggarang had the highest wind speed in the Southern Region. However, the map shows no significant distribution of high wind speed in the Central Regions. The highest wind speed throughout the Malaysian Peninsular was around 55.95 m/s, whereas the lowest was approximately 19.3 m/s. In addition, the distribution of damage was more evident at locations with higher wind speeds, as shown by the V_{site} wind hazard map (Figure 10).

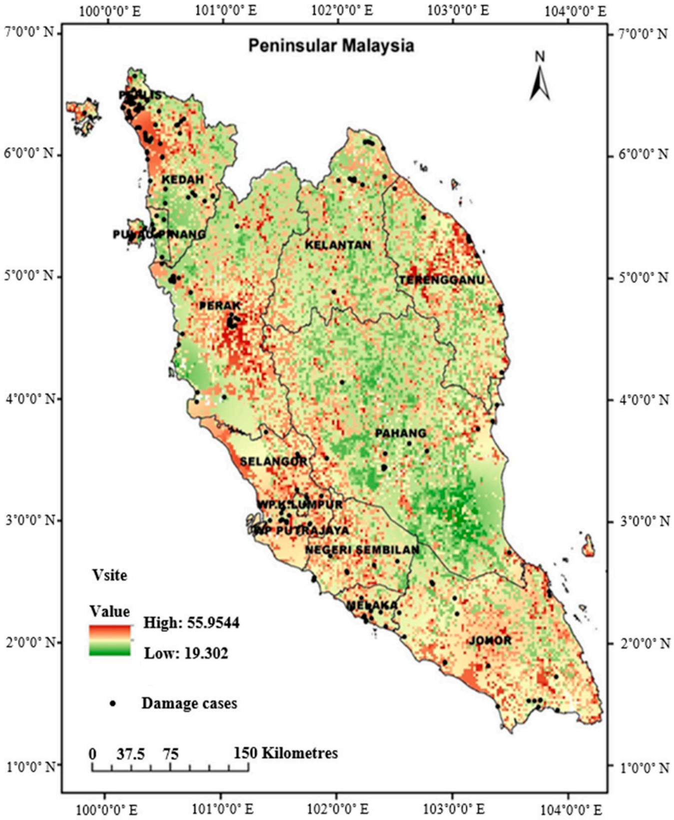


Figure 10. The V_{site} wind hazard map of Peninsular Malaysia.

3.4. Statistical Analysis and Validation

The statistical analysis using the Minitab® statistical software was conducted to evaluate the performance of the developed V_{site} wind hazard map for the whole Peninsular Malaysia and for each state.

Four different categories of wind speeds were identified: The basic wind speed (V_s), site wind speed (V_{site}), district wind speed ($V_{district}$), and subdistrict wind speed ($V_{mu\mathrm{kim}}$). Table 7 presents the comparison between the statistical analysis of the windstorm damage in Peninsular Malaysia. The mean wind speed, median wind speed, and skewers of the V_{site} were higher than those of the V_s map. The V_{site} reached 38.431 m/s, while the maximum V_s was only 31.599 m/s. The V_{site} maximum wind speed was higher by 17.8% compared to that of V_s due to the consideration of the Terrain Height and Hill Shape Multipliers. The windstorm occurrence increased with the increase of the terrain category and the decrease of the $M_{z,cat}$ coefficient. Moreover, it decreased with the increase of the slope degree. Thus, it can be concluded that the wind hazard map based on V_s predicted a lower potential wind speed compared to the V_{site} hazard map. The histogram analysis of the four wind speed categories is depicted in Figure 11.

Table 7. Statistical analysis of windstorm damage in Peninsular Malaysia.

Variable	Windstorm Damage	Mean (m/s)	Standard Deviation	Min (m/s)	Q1 (m/s)	Median (m/s)	Q3 (m/s)	Max (m/s)	Skewness
V_{site}	294	29.334	2.66	24.033	27.126	28.956	30.787	38.431	0.59
V_s	294	28.062	1.75	24.501	26.801	28.226	29.373	31.599	0.07
V_{mukim}	294	28.326	1.79	25.285	27.109	27.895	29.16	32.621	0.61
$V_{District}$	294	27.763	1.54	24.592	26.783	27.838	28.473	30.844	0.34

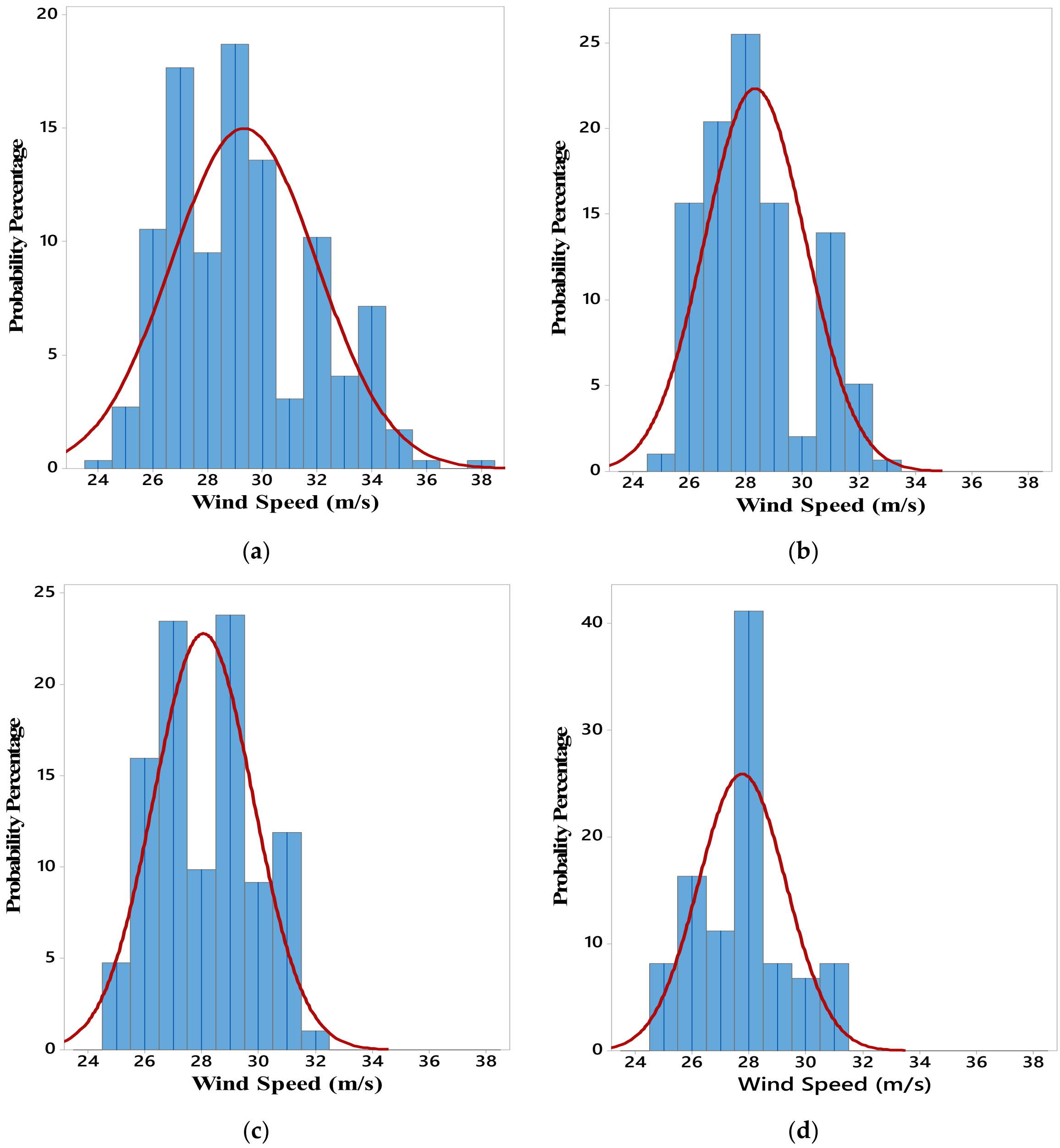


Figure 11. Histogram analysis of wind speed in Peninsular Malaysia: (**a**) V_{site}; (**b**) V_{mukim}; (**c**) V_s; (**d**) $V_{District}$.

Figure 12 shows the CDF of windstorm damage cases based on the 50-year return period adopted by this study. The percentage of the return period was calculated as follows:

$$Return\ Period\ (\%) = \left(1 - \frac{1}{T}\right) \times 100 \tag{7}$$

where T is equivalent to the number of years. Since T is 50 years, the return period probability is equal to 0.98, which is equivalent to 98%. When projecting this return period probability on the CDF graph, the predicted V_s and V_{site} were 31.66 m/s and 34.80 m/s, respectively. The CDF analysis also showed that the probability of intensity of V_{site} was higher than that of the V_s. This was attributed to the effects of the Terrain Height and Hill Shape Multipliers on the wind intensity, which were accounted for in the newly developed V_{site} map.

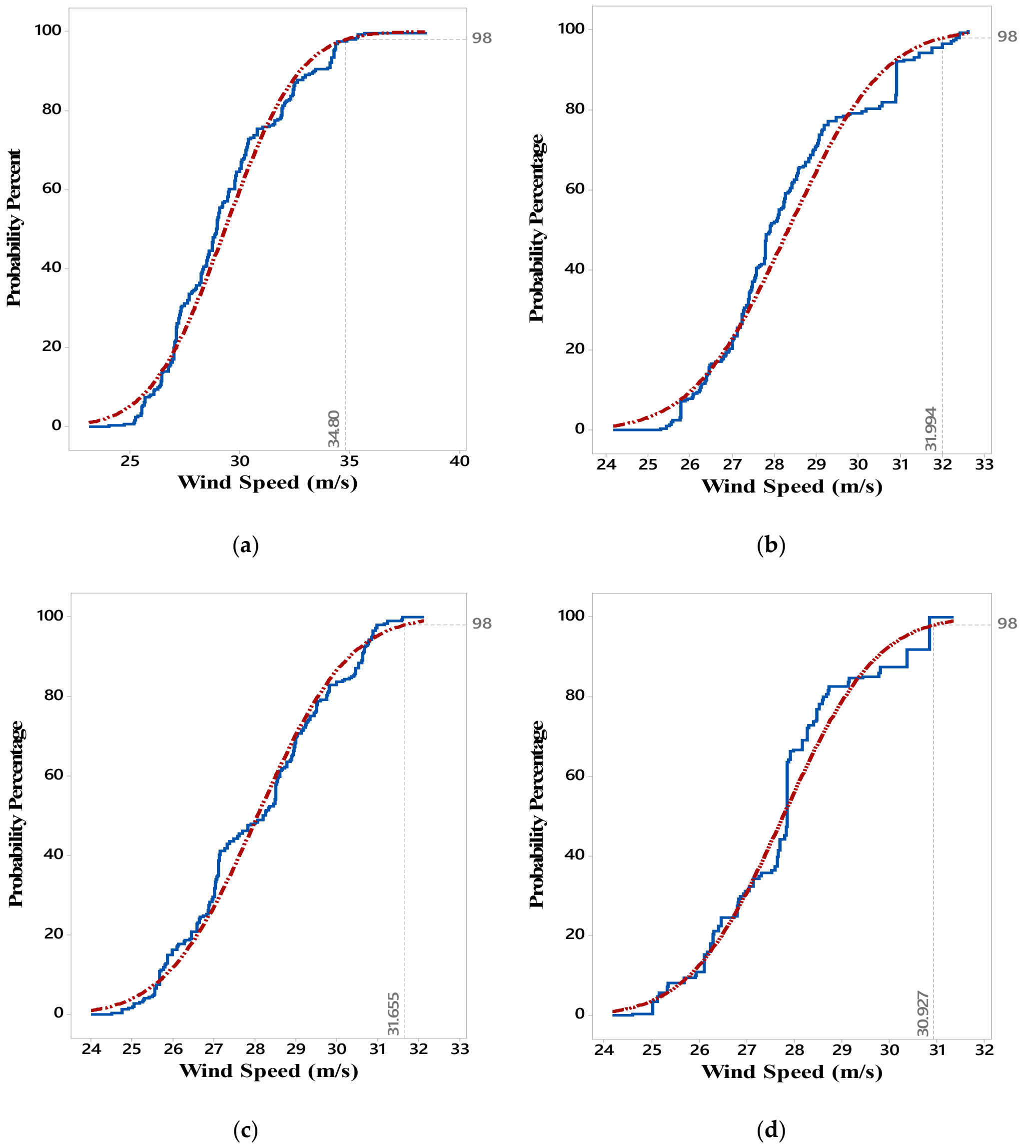


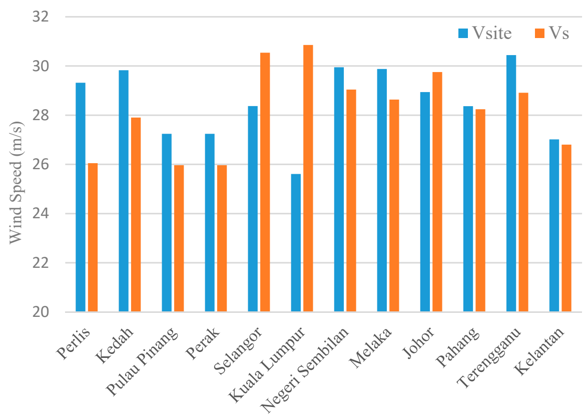
Figure 12. Cumulative Distribution Function (CDF) analysis of Peninsular Malaysia (**a**) V_{site}; (**b**) V_{mukim}; (**c**) V_s; (**d**) $V_{District}$.

The comparison of the 50-year return period wind speeds for all the states of Peninsular Malaysia is presented in Table 8. The results show that the wind speeds based on the V_s map were significantly lower than those of the V_{site} map for all states. The difference between the two predicted speeds varied from 3.54% to 17.79%. The highest difference was found in the state of Perlis (17.79%), whereas the lowest was in the state of Kelantan (3.54%). The overall difference in Peninsular Malaysia was around 9%. This clearly indicates that the V_s map underrated the wind hazard at a specific location in Peninsular Malaysia because it did not include the effects of the Terrain Height and Hill Shape Multipliers on the wind characteristics.

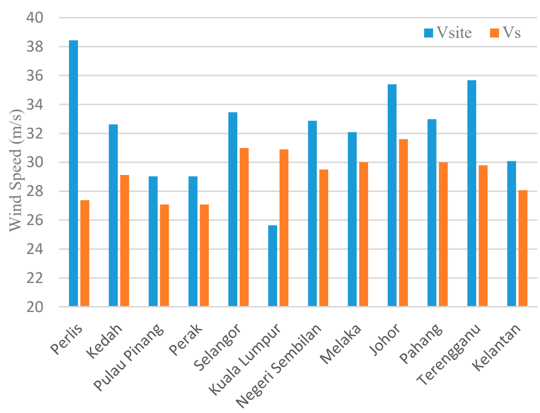
A summary of the statistical analysis of windstorm damage cases for each state in Peninsular Malaysia is presented in Appendix A. When comparing the mean of the V_s and V_{site} of each state as illustrated in Figure 13a, the mean of V_{site} was higher for all the states except Kuala Lumpur and Selangor. In addition, the comparison of the maximum wind speed of V_{site} was also higher except that of Kuala Lumpur (Figure 13b). This could be due to the nature of Kuala Lumpur and Selangor, which are more urbanized. The urban factor introduces a shielding effect to the surroundings, which is defined by MS 1553:2002 [10] as a shielding multiplier. This leads to the conclusion that the hazard map based on the V_s significantly underestimates the actual wind speeds, which results in the underestimation of the potential wind hazards.

Table 8. The 50-year return period wind speeds of Peninsular Malaysia.

State	The 50-year Return Period Wind Speed (m/s)		Difference (%)
	V_{site}	V_s	
Perlis	33.06	27.18	17.79
Kedah	34.67	30.09	13.21
Pulau Pinang	29.5	27.99	5.12
Perak	38.04	32.64	14.20
Selangor	33.43	31.78	4.94
Negeri Sembilan	35.17	29.9	14.98
Melaka	33.96	28.62	15.72
Johor	34.76	31.68	8.86
Pahang	33.29	30.61	8.05
Terengganu	35.64	30.58	14.20
Kelantan	29.38	28.34	3.54
Peninsular Malaysia	34.80	31.66	9.02



(**a**)



(**b**)

Figure 13. A comparison between wind speeds (V_s and V_{site}): (**a**) The mean; (**b**) the maximum.

4. Conclusions

A new wind hazard map for Peninsular Malaysia that considered the effects of LULC and the topographical conditions was constructed to overcome the drawbacks of the existing wind hazard map in the Malaysian Standard. The developed wind hazard map was constructed using the Geographic

Information Systems (GIS), and the results were properly compared with the past recorded wind damage cases that occurred in Peninsular Malaysia from 2009 to 2016 in order to validate its accuracy in the evaluation and prediction of potential wind hazards. From the results, the following conclusions can be drawn:

- The Northern Region of Peninsular Malaysia, consisting of five states, was the most affected, and experienced 159 windstorm damage cases, while the Eastern Region of the Peninsular came next with around 60 damage cases. They both suffered human loss beside the destruction of houses and vehicles. The Southern Region (50 cases) and the Central Region (20 cases) experienced similar damage to the previous two regions but did not experience any loss of human life. It was also noticed that the terrain conditions, as well as the economic development, had detrimental effects on the damage occurrence, whereas the population and the area did not contribute greatly to the occurrence of windstorm damage. However, it is not always consistent because the population has been reported as one of the contributors to the windstorm damages in other parts of the world.
- Based on the Terrain Height coefficient, 81.63% of the windstorms from 2009 to 2016 occurred in terrains with low $M_{z,cat}$ coefficients (1, 2, and 3) compared to 18.36% in terrains with high $M_{z,cat}$ (4, 5, and 6). Thus, it can be said that the windstorm occurrence increased with the increase of the terrain category and the decrease of the $M_{z,cat}$ coefficient. In other words, the roughness of the location plays a significant role in the occurrence of windstorms in Peninsular Malaysia. Similar results were reported by Lu et al. [26] and Tan and Fang [27] in their studies.
- The Hill Shape Multiplier (M_h) showed that the occurrence of windstorms is inversely proportional to the slope degree of the terrain. Having a plainer area such as the Northern and Eastern Regions subjected these locations to a higher windstorm damage.
- From the statistical analysis of the windstorm damages, it was found that the mean wind speed, median wind speed, and skewers of the V_{site} were higher than those of the Vs by 17.8% because of the Terrain Height and Hill Shape Multipliers. The windstorm occurrence increased with the increase of the terrain category and the decrease of the $M_{z,cat}$ coefficient. Moreover, it decreased with the increase of the slope degree. Therefore, it can be concluded that the wind hazard map based on Vs predicted a lower potential wind speed compared to the V_{site} hazard map.
- The CDF analysis also showed that the probability of intensity of V_{site} was higher than that of the V_s by almost 9%. This was due to the effects of the Terrain Height and Hill Shape Multipliers on the wind intensity that were considered in the newly developed V_{site} map.
- Overall, the results of the developed V_{site} wind hazard map proved that employing the current V_s wind hazard map to assess the windstorm risk is misleading as it underestimates the potential windstorm hazards in Peninsular Malaysia. Thus, it is highly recommended to use the newly developed V_{site} map. This newly developed map is a novel contribution to the wind science, especially in tropical countries, where major monsoon periods exist. The map is a clear enhancement of the existing wind map used in Peninsular Malaysia. The authors hope that their developed map will be incorporated into the Malaysian Standard by the relevant authorities to enhance the wind risk assessment.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Summary of the statistical analysis of windstorm damage cases for each State in Peninsular Malaysia.

State	Variable	Windstorm Damage	Mean (m/s)	Standard Deviation	Min (m/s)	Q1 (m/s)	Median (m/s)	Q3 (m/s)	Max (m/s)	Skewness
Perlis	V_{site}	48	29.315	1.832	25.178	28.748	29.089	29.769	38.431	2.210
	V_s	48	26.047	0.554	25.000	25.668	25.862	26.580	27.379	0.620
	V_{mukim}	48	28.769	1.458	25.504	27.781	28.329	29.462	32.205	0.430
	$V_{District}$	48	27.838	0.000	27.838	27.838	27.838	27.838	27.838	-
Kedah	V_{site}	49	29.828	2.358	25.268	27.950	30.363	31.908	32.619	−0.420
	V_s	49	27.902	1.067	25.591	27.037	28.248	28.948	29.124	−0.730
	V_{mukim}	49	29.243	1.989	26.442	27.548	28.484	31.450	32.621	0.530
	$V_{District}$	49	28.288	1.724	25.149	26.282	28.260	30.365	30.365	−0.260
Pulau Pinang	V_{site}	20	27.243	1.100	24.740	26.451	27.039	27.711	29.030	0.190
	V_s	20	25.965	0.984	24.501	24.941	26.447	26.880	27.083	−0.250
	V_{mukim}	20	27.899	1.633	26.263	26.459	27.486	28.755	31.334	1.140
	$V_{District}$	20	26.613	1.594	25.112	25.322	25.339	28.473	28.473	0.330
Perak	V_{site}	20	27.243	1.100	24.740	26.451	27.039	27.711	29.030	0.190
	V_s	20	25.965	0.984	24.501	24.941	26.447	26.880	27.083	−0.250
	V_{mukim}	20	27.899	1.633	26.263	26.459	27.486	28.755	31.334	1.140
	$V_{District}$	20	26.613	1.594	25.112	25.322	25.339	28.473	28.473	0.330
Selangor	V_{site}	17	28.370	2.465	25.491	26.095	28.226	29.418	33.455	0.870
	V_s	17	30.536	0.607	28.966	30.384	30.848	30.913	30.985	−1.680
	V_{mukim}	17	27.983	0.883	27.109	27.109	27.871	28.423	30.078	0.800
	$V_{District}$	17	28.531	0.429	28.168	28.168	28.406	28.868	29.431	0.990
Kuala Lumpur	V_{site}	3	25.609	0.538	24.547	25.547	25.640	25.640	25.640	−1.730
	V_s	3	30.854	0.648	30.780	30.780	30.892	30.892	30.892	−1.730
	V_{mukim}	3	27.799	0.000	27.799	27.799	27.799	27.799	27.799	-
	$V_{District}$	3	27.663	0.000	27.663	27.663	27.663	27.663	27.663	-

Table A1. *Cont*.

State	Variable	Windstorm Damage	Mean (m/s)	Standard Deviation	Min (m/s)	Q1 (m/s)	Median (m/s)	Q3 (m/s)	Max (m/s)	Skewness
Negeri Sembilan	V_{site}	10	29.945	2.544	25.943	28.168	29.497	32.509	32.869	−0.170
	V_s	10	29.038	0.421	28.354	28.607	29.133	29.385	29.497	−0.380
	V_{mukim}	10	28.137	1.739	25.285	27.406	27.896	28.551	32.319	1.300
	$V_{District}$	10	27.998	0.560	26.860	27.597	28.263	28.373	28.602	−0.890
Melaka	V_{site}	15	29.875	1.989	26.138	28.512	28.541	31.967	32.087	−0.160
	V_s	15	28.634	0.683	27.000	28.512	28.521	28.649	30.000	0.190
	V_{mukim}	15	28.129	0.927	26.728	27.010	28.540	29.000	29.179	−0.290
	$V_{District}$	15	27.974	0.559	26.500	27.835	27.920	28.010	29.000	−0.500
Johor	V_{site}	30	28.939	2.834	24.033	26.750	28.877	29.812	35.391	0.950
	V_s	30	29.750	0.941	28.512	29.211	29.495	29.970	31.599	0.880
	V_{mukim}	30	27.879	0.848	26.392	27.337	27.831	28.567	29.131	−0.210
	$V_{District}$	30	27.714	0.775	26.451	27.255	27.698	28.514	28.705	−0.440
Pahang	V_{site}	21	28.363	2.399	25.229	27.001	27.142	30.050	32.982	0.770
	V_s	21	28.241	1.152	27.001	27.073	27.824	29.448	29.994	0.330
	V_{mukim}	21	27.078	0.988	25.432	26.244	27.001	28.107	28.861	0.240
	$V_{District}$	21	26.010	1.034	24.592	25.022	25.683	27.126	27.531	0.280
Terengganu	V_{site}	14	30.443	2.529	27.326	28.789	29.350	32.513	35.676	0.670
	V_s	14	28.911	0.811	27.326	28.719	28.859	29.757	29.790	−0.890
	V_{mukim}	14	29.375	2.070	25.922	28.013	29.338	31.755	31.755	−0.340
	$V_{District}$	14	27.656	1.471	26.399	26.399	26.899	29.812	29.812	0.840
Kelantan	V_{site}	25	27.013	1.149	25.533	26.351	27.109	27.196	30.079	1.210
	V_s	25	26.802	0.748	25.533	26.338	27.109	27.112	28.067	−0.660
	V_{mukim}	25	26.018	0.512	25.552	25.776	25.776	26.064	27.793	2.210
	$V_{District}$	25	26.363	0.508	26.096	26.096	26.096	26.276	27.659	1.980

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