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Original Article

INDICATOR BASED ASSESSMENT OF INTEGRATED FLOOD VULNERABILITY INDEX FOR BRUNEI DARUSSALAM

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Abstract: Since the beginning of human civilization, the flood is always connected with extensive destruction of properties and loss of lives. The intensity of flood-related disasters is increasing day by day due to the rapid increase in development activities, changes in land-use land-cover, population growth, unplanned urbanization, and above all, the driving force resulting from climate change and climate variability. Therefore, researchers are paying increased attention to floods with particular focus on flood vulnerability. The present study is a pioneer attempt on indicator-based flood vulnerability assessment for Brunei Darussalam. In this study, an integrated approach towards vulnerability assessment has been proposed, considering hydrological, environmental, social, and economic aspects of different districts of Brunei Darussalam. Indicators are generated and incorporated to visualize the vulnerability map of the country. The findings of the study can be used to identify the vulnerability status of different regions in Brunei, used to reduce the vulnerability and also to minimize disaster risk by allocating more resources for vulnerable districts. The results of the study will also be helpful in deriving better disaster management strategies for the country.

Keywords: vulnerability; index; indicators; assessment; map.

1. Introduction

The management and mitigation of flood hazard is a multidimensional task (Ayala et al., 2020; Jaiswal et al., 2020). It requires knowledge and integration of various disciplines such as hydrology, meteorology, geology, sociology, economics, statistics, demographic studies, policy, and planning (Karmaoui et al., 2016; Prinos, 2008). The influences of different aspects of the livelihood of people like social, cultural, and economic affect the vulnerability of a region directly and indirectly (Munyai et al., 2019; Nasiri et al., 2019; Rehman et al., 2019; Žurovec et al., 2017). Moreover, the hilly and coastal areas are likely to be more vulnerable due to frequent and intensive flash floods under various climate change scenarios (Costa and Machado 2017; Guillard-Gonçalves and Zêzere 2018). As such, it is essential to study the impact of climate change on the vulnerability index of a country. The concept of vulnerability is, therefore, a multidimensional factor that has a strong correlation to climate change, among other factors. It includes risks, sensitivity, natural hazards, etc. In general, the vulnerability comprises of the following characteristics:

Multidimensional: consist of many factors like physical, economic, social, environmental, as shown in Figure 1 (Dottori et al., 2018; Lee et al., 2013).

Dynamic: change of vulnerability over time (Dottori et al., 2018; Science, 2018).

Scale-dependent: vulnerability can vary from household to community, community to districts and districts to a country (Kumar and Bhattacharjya 2020; Singh et al. 2014).

Site-specific: different for each country or state.

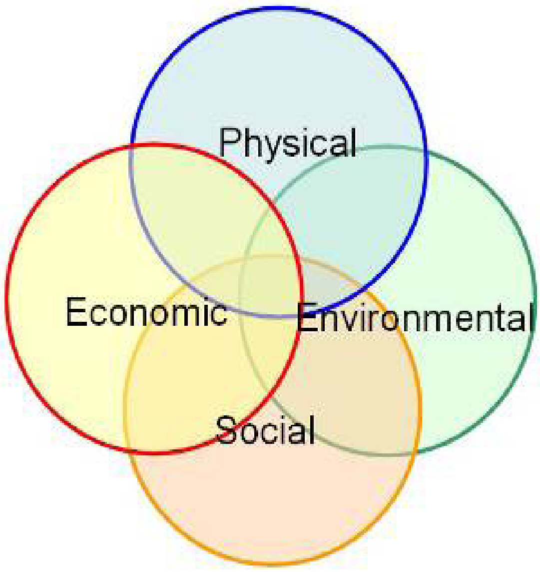


Fig.1: Multidimensional nature of Vulnerability (Balica et al., 2017)

Many researchers have extensively studied about flood hazards and their mitigation, including flood vulnerability assessment. A comprehensive and multidimensional vulnerability is defined by Birkmann (2006). According to him, indicators and criteria used for vulnerability measurement should have physical, economic, and social relations within the area of interest (Kha et al., 2008; Villordon, 2015). Balica et al. (2012) explained the flood vulnerability with an indicator based method. This indicator-based method, which is used to calculate Flood Vulnerability Index (FVI), depends upon geomorphological characteristics such as shape, size, area of a river catchment, sub-catchment, slope and topography, drainage network, rural/urban area and coastal area (Fernandez, Mourato, Moreira, et al., 2016; Hajar Nasiri et al., 2016). Atkins et al. (1998) suggested a composite vulnerability index for developing/island countries. They computed the integrated vulnerability index for 110 developing countries. The results indicated that small countries are more likely to be vulnerable as compared to large countries (Fernandez, Mourato, Moreira, et al., 2016; Karmaoui et al., 2016). Monika Blistanova et al. (2016) assessed the flood vulnerability based on different criteria for the Bodva river basin in the eastern part of Slovakia. They used hydrological factors, such as discharge and inundation depth of the basin along with the geomorphological properties of the basin, like slope and soil type, etc. All these indicators are analyzed and incorporated in GIS to classify the study area in four classes – acceptable, moderate, undesirable, and unacceptable vulnerability zone (Huang et al., 2005; Sadeghi-Pouya et al., 2017). Birhanua et al. (2016) evaluated the vulnerability of Addis Ababa due to rapid urbanization and climate change. They used the SWAT model to obtain the peak discharge and incorporated the peak discharge as one of the indicators. The future rainfall was predicted by using the General Circulation Models (GCM), and land cover data was generated from the Landsat images. The results showed that there is a considerable increase in discharge due to climate change, which eventually increases the vulnerability (Lee et al., 2013). Kaspersen et al. (2017) elaborated the multidimensional aspects of flood vulnerability, considering social, economic, and hydrological aspects. Their analysis was based on an integrated approach for all the factors of flood vulnerability, known as the Danish Integrated Assessment System (DIAS). This DIAS is capable of evaluation of risk due to flooding from severe precipitation, and the model is applied in the city of Odense, Denmark (Rimba et al., 2017).

1.1. Study on Flood vulnerability index for Brunei Darussalam

Ndah et al. (2017) proposed a theoretical aspect of vulnerability assessment in Brunei Darussalam based on the Pressure and Release (PAR) model. They found that Hazard-risk assessment for the country is crucial due to the topographic condition and also due to the impact of climate change. They also reported the absence of a vulnerability mapping system in the country (Banyouko et al., 2017; Ndah et al., 2016). The report published by disaster management agency, reveals that floods remain the most prominent and economic loss in Brunei Darussalam, with an annual loss of about USD 37.31 million (Profile et al., n.d.). An official report based on disaster mitigation provides information on the general causes and effects of floods. It also explains the flood mitigation measures that are in place in Brunei Darussalam (Officials & Societies, 2015). Apart from these reports, there is hardly any study that has been carried out for the assessment of vulnerability in Brunei Darussalam. The growth of economic activities resulting from Methanol industry, Fertilizer plant in Sungai Liang and the Petrochemical industry in Pulau Muara Besar and potential growth for agricultural activities (Shams et al., 2015) requires an Integrated Water Resources Management (IWRM) approach (Shams and Nasrin, 2019) with development of flood vulnerability index for Brunei Darussalam. The present study emphasized on estimating the integrated flood vulnerability index of Brunei Darussalam, considering social, economic, environmental, and hydrological factors together. The limitation with the present study is the unavailability of data at the mukim (village) level. Therefore, this study focuses on developing an integrated flood vulnerability index at the district level.

The review of the literature shows that the assessment and evaluation of flood vulnerability with an integrated approach have not been carried out in many countries in the world, including the southeast ASEAN country. The vulnerability describes the extent to which a population, human settlement, community/society is exposed to hazards like flooding, landslides, earthquake, etc. The coastal flood and flash floods are very common phenomena in Brunei Darussalam due to intensive short-duration rainfall. Generally, the flash flood is occurring due to cloud bursting, which is very common in South Asia such as Bangladesh, India, Sri Lanka, etc. However, in Brunei Darussalam, the flood is not only occurring due to cloud bursting but also due to other factors such as backflow resulting from tidal surge. This has aggravated the situation further with obstructions in the drainage system. Since the vulnerability is site-specific, it is especially important to note down the parameters that describe different components of vulnerability along with their measurement at the sub-basin level or basin level, national level, or regional level. It is also essential to know how to link them with hazard parameters for obtaining an integrated vulnerability assessment. Hence, all the factors of vulnerability, as discussed above, are further classified into three different categories: exposure, susceptibility, and resilience.

Exposure Index: (EI)

Exposer describes the condition of people, infrastructure, services, production places settled in hazard-prone or flood-prone areas (Feloni et al. 2020; Kumar and Bhattacharjya 2020). This can be due to the shift in climatic parameters or variation in climatic situations. For the present study, a total of twenty variables, including the hydrological factors, also called as indicators were taken into consideration to study the district-wise exposure to flood and their impacts. For generating the exposure index, we combined all the indicators related to floods and landslides.

Susceptibility Index (SI)

Susceptibility is defined as the elements present within the system that determine the chances of being harmed at the time of hazards (Khajehei et al., 2020; Pricope et al., 2019). For the present study, twenty-one variables, i.e., indicators, were taken into consideration to calculate the district-wise susceptibility to flooding. The indicators considered in this study are listed in Table 1, along with their relationship with the vulnerability.

Resilience Index (RI)

The capacity of a social system to counter and overcome any adverse event is defined as resilience (Ayala et al. 2020; Nasiri et al. 2019; Khalili et al., 2015). It includes the strength of the system to absorb impacts, coping with the event as well as post-event adaptive response. In general terms, it helps the system's ability to rearrange, modify, and discover the hazard or any disaster. Resilience can also be understood as the coping capability of a system during flood and restoration ability after the flood. In the present study, thirteen indicators were taken to examine the district-wise resilience to flood and their impacts in terms of forest cover, communication penetration rate, awareness, and past experience, etc.

As vulnerability is a function of exposure (E), susceptibility (S) as well as resilience (R), an integrated approach has been applied to assemble all these factors into a single value (Karmaoui et al., 2016; Kayulayula & Banda, 2015; Teng et al., 2017). The selection of indicators is the most critical task for generating a reliable vulnerability index. So, the selection of different indicators is made based on past studies and expert judgment. The selected indicators amongst social factors (population density, elderly population, children population, literacy rate, disability, female-headed house, etc.), economic factors (unemployment, migration rate, electricity coverage, etc.), hydrological factors (rainfall pattern, distance from the riverside, flood frequency), environmental factors (land use, urbanization, forest cover), were taken into due consideration to accurately represent the vulnerability of the area.

Table 1: *Indicators considered in this study, along with their relationship with vulnerability.*

S.No	Indicators	Definition	How to affect the vulnerability	Indicator Sub-head	Source/ References
1	Inactivity Rate (%)	The proportion of the population that is not in the labour force	+	S	(Data-da-lam-penerbi-tan, n.d.)
2	Waste land of the total geographical area (%)	Total percentage of barren land of the total geo-graphical area	+	E	(Agency, 2015)
3	No of tourist visited (2010-2018)	The tourist coming in the country and they don't know the geographic condition of the visiting country	+	E	(Data-da-lam-penerbi-tan, n.d.)
4	Forest fire (total affected area, ha) up to 31/12/2018.	Forest fire results into burnt land/waste land unfit for any activities	+	E	(Morani, 2017)
5	Urbanized area of the total area (%)	More urbanized area means more runoff	+	E	(Ndah et al. 2016; Wagh-wala and Agnihotri, 2019)
6	No. of HEP(hydroelectric power), All types	If the hydropower plant is more that means more dam for water storage with high capacity	+	E	(Profile et al., n.d.)
7	Outward migration, share of the state population (%)	If more population is going outside the country, in case of disaster very less person can help others	+	E	(Data-da-lam-penerbi-tan, n.d.)
9	Area with altitude more than 3000 m (%)	More altitude, more chances of landslide	+	E	(Data-da-lam-penerbi-tan, n.d.)
10	Landslide zone area of the total area (%)	More landslide area, more affected at the time of disaster	+	E	(Data-da-lam-penerbi-tan, n.d.)
11	Unemployment (%)	Unemployment leads to peoples crowded at a single place for needs during any natural disasters and so recovery time is very slow in case of disaster	+	E	(Data-da-lam-penerbi-tan, n.d.)
12	Cultural heritage	No. of historic buildings, the museum in the state, at the time flood highly chance to get affected	+	E	(Morani, 2017)
13	Population close to the coastline	Percentage of the population living near to coast and mostly affected at time costal flood	+	E	(Morani, 2017)
14	Growth of population in the last 10 years near the coastline (%)	If more growth (%) then more population density near cost line	+	E	(Data-da-lam-penerbi-tan, n.d.)
15	Low cost building (%)	Low cost buildings have higher chances to collapse at the time of disaster	+	E	(Data-da-lam-penerbi-tan, n.d.)
16	Population density	More population in an area, very tough to exca-vate the place at the time of disaster	+	S	(Data-da-lam-penerbi-tan, n.d.)
17	Disabled people	They are not able to move at a safe place at the time of disaster by themselves	+	S	(Data-da-lam-penerbi-tan, n.d.)
18	Elderly population	They are not able to keep themselves at a safe place at the time of disaster	+	S	(Data-da-lam-penerbi-tan, n.d.)
19	Children under 15	They are not able to move at a safe place at the time of disaster by themselves	+	S	(Data-da-lam-penerbi-tan, n.d.)
20	Agriculture workers	Generally, they are dependent on agriculture and mostly economic weak and highly targeted at the time of the flood	+	S	(Data-da-lam-penerbi-tan, n.d.)
21	Literacy rate	If the people are more literate, they can take pre-ventive measures during and after a disaster	-	S	(Data-da-lam-penerbi-tan, n.d.)
22	Large Household size	Large household size means living rooms more than two rooms and having more than one floor to accommodate more people and in case of failure more people will be affected	+	S	(Data-da-lam-penerbi-tan, n.d.)

23	Number of houses with poor material	The houses with poor building material are subjected to collapse/failure easily at the time of disaster	+	S	(Data-da-lam-penerbi-tan, n.d.)
24	Poverty Rate	Higher the poverty rate means more economical weak people and greatly affected during and after the flood	+	S	(Data-da-lam-penerbi-tan n.d.; Solin et al. 2019)
25	Decadal growth rate	More growth rate, more peoples are living at a place	+		(Assessment & Issues, n.d.)
26	Female Population	Females are taking care of other family members and the time of disaster they firstly prevent other members of the house and less attention towards own safety	+	S	(Data-da-lam-penerbi-tan, n.d.)
27	Total no of the river in the state	More river means more chances of flood at the time of high rainfall	+	S	(Data-da-lam-penerbi-tan, n.d.)
28	Total no of industries unit in the state	If industrial units are more in a place that more peoples are living there and will be affected more at the time of disaster	+	S	(Data-da-lam-penerbi-tan, n.d.)
29	Human development index	More HDI means peoples are economically sound and reduces the impact of disaster	-	S	(Data-da-lam-penerbi-tan, n.d.)
30	% of Forest cover of total geographical area(ha)	More forest area can reduce the runoff and soil erosion	-	R	(Data-da-lam-penerbi-tan, n.d.)
31	Structural measure for flood protection	If the transportation facility is well, they can be used at the time of evacuation in case of disaster	-	R	(Ndah et al., 2016)
32	The total length of ap-proaching road linked with major district road(km)	If the transportation facility is well, they can be used at the time of evacuation in case of disaster	-	R	(Department of Statistics Malaysia, 2017)
33	Communication penetra-tion rate (%)	More communication facilities can spread the emergency condition amongst the people at the time of emergency	-	R	(Data-da-lam-penerbi-tan, n.d.)
34	The area having electricity (%)	If electricity is available, in case of emergency, the evacuation process can be smooth	-	R	(Data-da-lam-penerbi-tan, n.d.)
35	Village connected with pucca roads (%)	If the transportation facility is well, they can be used at the time of evacuation in case of disaster	-	R	(Data-da-lam-penerbi-tan, n.d.)
36	No. of transport vehicles (registered vehicle of all types/1000 km2)	If the transportation facility is well, they can be used at the time of evacuation in case of disaster	-	R	(Data-da-lam-penerbi-tan, n.d.)
37	No. of hospital / 0.1 million population	The hospital can be used in case of disaster to treat the people effectively	-	R	(Data-da-lam-penerbi-tan, n.d.)
38	No. of flood forecasting / warning system/ Flood hazard maps	The warning system can alert the people about coming hazard	-	R	(Data-da-lam-pener-bitan n.d.; Henriksen et al., 2018)
39	Awareness about Hazard	If the group of peoples knows about the hazard, they can prepare themselves in case of emergency	-	R	(Nottingham, 2014), SUR-VEY*
40	Past Experience about Hazard	If the peoples have experience about the hazard, in future they can tolerate and take preventive measures in case of emergency	-	R	(Tan et al., 2017), SUR-VEY*
41	The total length of canaliza-tion in the different part of the state	They can be used to move the extra water in case of flooding	-	R	(Assessment and Issues n.d.)
42	People having flood insur-ance (%)	The insurance company can fulfill the loss in case of flood	-	R	(Mahidin, 2017)
43	Open space land (%)	Can be used as grouping center or shelter at the time of hazard	-	R	(Mahidin, 2017)
44	Average Proximity to the river of different districts in a state (m)	If a place is near to river bank the place is highly affected in case of flood	+	HE	(Abdullah, 2013), Google earth

45	Average rainfall(mm) in Monsoon season in last 25 years	More rainfall can cause flood events frequently	+	**HE**	(Banyouko et al., 2017; Ratnayake, 2018)
46	Flood frequency in a flash flood (≥ 250 cumecs)	If the frequency is more than flood can come at very less time interval	+	**HE**	(Morani, 2017; Profile et al., n.d.)
47	Maximum rainfall (mm/day)	More rainfall can cause flood events frequently	+	**HE**	(Morani, 2017; Profile et al., n.d.)
48	Avg. heavy rainfall days, (Rainfall is > 170mm)	More rainfall can cause flood events frequently	+	**HE**	(Morani, 2017; Profile et al., n.d.)
50	Coastline length	If the costal length is more, there is a high probability to come flood near coastal areas	+	**HE**	(Morani, 2017; Profile et al., n.d.)
51	No. of cyclone in the last 15 years	More chances that the same disaster will happen again	+	**HE**	(Morani, 2017; Profile et al., n.d.)
52	Flood duration	If the duration of flood is more, the destruction due to this is more	+	**HE**	(Morani, 2017; Profile et al., n.d.)

(+ = higher %, higher vulnerability, - = higher %, lower vulnerability), (E= Exposure, S= Susceptibility, R= Resilience, HE = Exposure under hydrological factor)

(*Survey = a total of 10 families, consist of around 70 peoples in each district of Brunei)

1.2 Data collection approach for the survey

In the vulnerability assessment, a probability proportional to respective size (PPRS), as described by the (Alnaimat et al., 2017; Antwi et al., 2015) was applied to determine the size of sample in different district of Brunei.

2. Case study

Brunei Darussalam is located on the northwest coast of the island of Borneo in South East Asia between latitude 4°30'N and longitude 114°04'E. It has a total land area of 5,765 km^2 and a coastline of 168 km bounded by the South China Sea on the north and the East Malaysian states of Sarawak and Sabah on the east and west, respectively. Brunei Darussalam being a tropical country, very rich in biodiversity and well known for its pristine rain forests, has its unique importance in the region, particularly in relation to eco-tourism. It has some historical places such as water villages (Kampong Ayer) located on Brunei River and Istana Nurul Iman Palace, the palace of the light of faith, which attract not only local visitors but also foreigners (Tiquio et al., 2017). Water villages have a history of more than one thousand years. Throughout the year, the average temperature can range from 28°C (82°F) to 32° (89°F) during the day. The population of Brunei in 2014 was 411,900, with an annual growth rate of 1.27%. Brunei Darussalam has an equatorial climate influenced by the monsoon systems known as northeast monsoon and southwest monsoon. The country generally experiences wet, humid and hot conditions throughout the year, with an average annual rainfall of 3,000 mm. Brunei Darussalam is experiencing a rapid change in climatic conditions, particularly in terms of temperature and the amount of rainfall received annually. The field survey revealed that the elders often complained about the rising temperature as compared to the temperature when they were young (Shams et al., 2015). This has been further validated by the observed climate change trends in Brunei Darussalam, which include an increase in the average temperature of 0.031°C and rainfall of 26.16 mm annually (Hassan et al., 2016). Brunei Darussalam is expected to experience more warming and less frequent precipitation events but with a possibility of intensified and drastically high rainfalls in the future (Hassan et al., 2017). The high-intensive rainfall will cause flash flood inundating low lying and coastal areas. The study area, along with its four districts, is shown in Figure 2, and basic information like area of different districts, the river basin *etc.* are shown in Figure 3.

Fig.2. *Location of Brunei Darussalm*

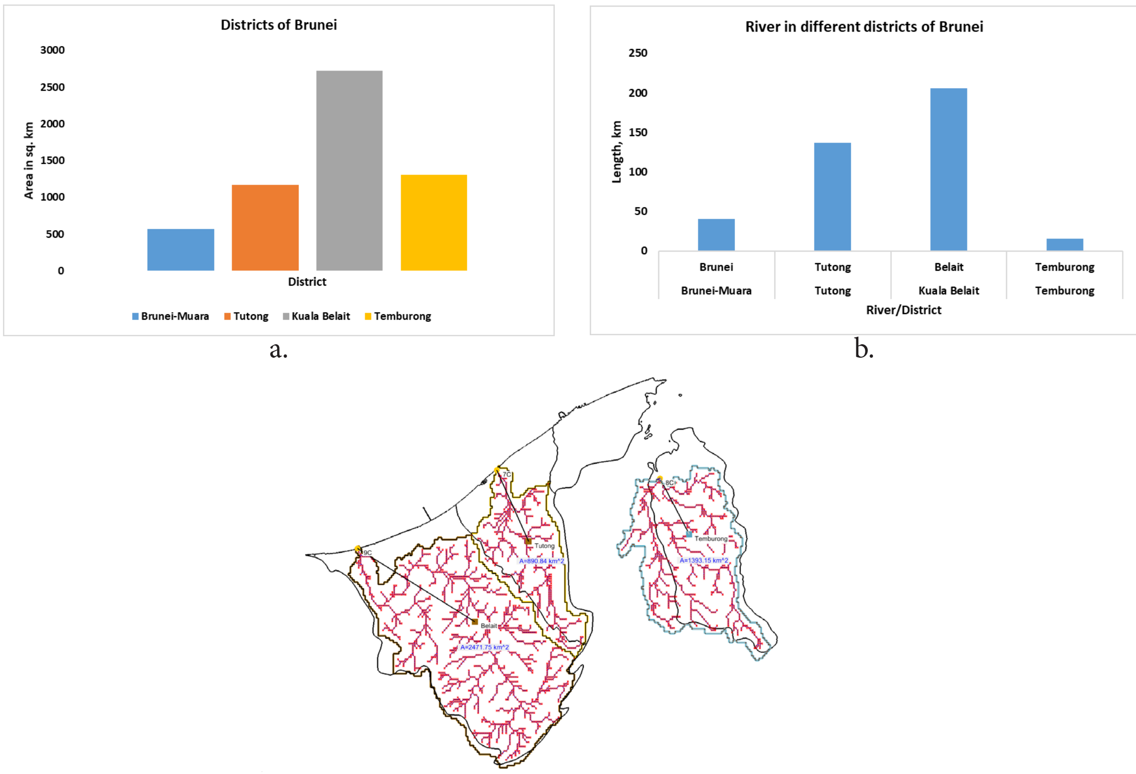


Fig. 3(a-c): *Brunei-districts with their area and a major river*

There are four major river basins in Brunei Darussalam. The length and their catchment area are shown in Fig. 3(b-c). These river basins are flowing directly to the South China Sea through their main channels. Out of four, two of the river basins are considered prone to regular flooding, especially the Tutong River basin (Assessment & Issues, n.d.; Ghani et al., 2012; Ndah et al., 2016; Pengairan & Saliran, 1987). Fig. 4 shows some photographs taken at the time of the flood in different parts of Brunei Darussalam.

Figure 4. *The flooded area at Tutong and Brunei-Muara in Brunei Darussalam during the flood*

3. Methods

The flow diagram indicating all the steps towards the development of an effective flood vulnerability index is shown in Fig.5. The different indicators of vulnerability relevant to the study area are selected, and the value of the indicator is normalized to prepare the exposure, susceptibility, and resilience index. All indexes are incorporated in ArcGIS10.4 to get the index map. As seen in literature, various methods are available to generate the vulnerability index value such as, based on pixel value using image analysis (Fernandez, Mourato, & Moreira, 2016; Frigerio et al., 2018), using Artificial Neural Network (ANN) and fuzzy logic (Antwi et al. 2015; Kumar et al. 2012; Lee et al. 2013; Prasad and Narayanan 2016; Science 2018; Cai et al. 2019) and quantitative method as used in the present study (Adger, 1998; Gebreyes & Theodory, 2018; Kissi et al., 2015; Wijaya & Hong, 2018).

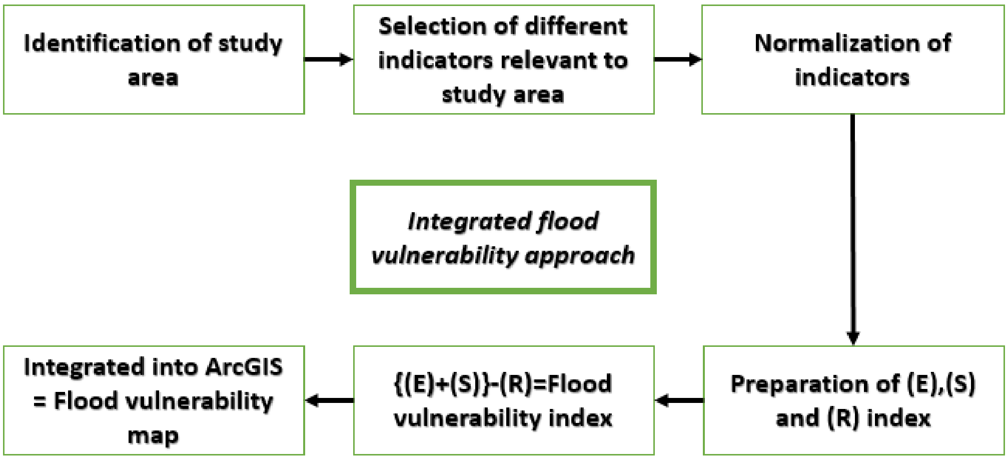


Figure 5. *Flow diagram for integrated flood vulnerability index.*

Two types of operative association are possible between vulnerability and their indicators. Firstly, the vulnerability increases with the increase (or decrease) in the value of the indicator or vice versa. In this study, two formulas are used to normalize indicators, depending on their operative association with vulnerability. If the vulnerability increases with the factors, the normalization is done using the following equation.

$$Y_{ij} = \frac{\{X_j - Min(X_j)\}}{\{Max(X_j) - Min(X_j)\}} \tag{1}$$

On the other hand, if the vulnerability decreases with the factors, the normalized score is calculated as:

$$Y_{ij} = \frac{\{Max(X_j) - X_j\}}{\{Max(X_j) - Min(X_j)\}} \tag{2}$$

Where, X_{ij} is the value of jth indicator $(j = 1,2,\ldots,3)$ in the ith district $(i = 1,2,\ldots,3)$ and Y_{ij} is the matrix corresponding to the normalized score. It has been already mentioned that the estimated value of Y_{ij} lies between 0 and 1. The value 1 is corresponding to that district with maximum value, and 0 is corresponding to the district with the minimum value.

After calculating the normalized scores, the composite index is formed by giving an unequal weight to all indicators. In most of the previous work, several methods were used to give weight to indicators. These methods are either providing equal weights, i.e., a simple average of the scores provided by Patnaik and Narain Methods (Rimba et al., 2017) or unequal weights, i.e., by expert judgment as used by Iyengar and Sudarshan (Kissi et al. 2015; Godfrey et al. 2015). The weight can also be provided by multivariate statistical techniques, i.e., by the principal components and cluster analysis method (Bahinipati, 1999; Balica et al., 2017; Bhadra et al., 2009; Chakraborty & Joshi, 2017; Marques et al., 2015).

In this study, we used the Iyengar and Sudarshan method (Adger, 1998; Kissi et al., 2015) to give weight to all indicators contributing to vulnerability. Iyengar and Sudarshan (1982) (Fernandez, Mourato, Moreira, et al., 2016; Kha et al., 2008) obtained an equal index from multidimensional data, and the index was used to rank the districts/states in terms of their financial enforcement. The proposed method is statistically reliable and equally satisfactory for the development of the proposed index. In Iyengar and Sudarshan method, the value of the indicators is hypothesized to change inversely with the variance. The weight of each factor W_j is determined by:

$$W_j = \frac{c}{\left[Var\left(X_j\right)\right]^{1/2}} \tag{3}$$

Where c is a normalizing constant i.e.

$$c = \left(\sum 1 \Big/ \left[Var\left(X_j\right)\right]^{1/2}\right)^{-1} \tag{4}$$

The composite indicator for flood vulnerability factors (exposure, susceptibility, and resilience) for the ith state was obtained as:

$$Y_i = \sum W_j Y_j \tag{5}$$

Where Yi is the composite indicator of ith state, Wj is the weight for each indicator lies between 0 and 1, ∑Wj = 1, and Yij is the normalized scores of indicators.

To ensure that the indices calculated for each vulnerability factor can be compared, the sum for each factor of exposure, susceptibility, and resilience are divided by their respective number of indicators that describe each vulnerability factor. The composite vulnerability index for the exposure factor is given as:

$$C_{ex} = \left\lfloor \sum W_j Y_j \right\rfloor \Big/ n \tag{6}$$

Where Cl_{ex} is the composite vulnerability index of exposure factor, Wj is the weight of an indicator, Yij is the normalized value of exposure indicator, n is the number of indicators. Similarly, we calculate susceptibility and resilience factors, i.e., Cl_{sus}, and Cl_{rei}. Finally, the integrated flood vulnerability index can be given as

$\boldsymbol{IFVI = Cl_{ex} + Cl_{sus} + Cl_{hydro} - Cl_{rei}}$ (Feloni et al., 2020; Kumar & Kumar Bhattacharjya, 2020a; Line, 1999; Hajar Nasiri et al., 2016) **(7)**

Where, $\boldsymbol{Cl_{ex}}$ is the exposure index, $\boldsymbol{Cl_{sus}}$ is the susceptibility index, $\boldsymbol{Cl_{hydro}}$ is the exposure index for hydrological factors and $\boldsymbol{Cl_{rei}}$ is the resilience index.

4. Results and discussion

Exposure index*:*

As explained earlier, that exposer defines the condition of people, infrastructure, accommodations, production capacities settled in hazard-prone or flood-prone areas. For the present study, a total of twenty variables (out of which 7 indicators are as hydrological exposure), also called indicators, were taken to examine the state-wise exposure to flood and their impacts. For generating the exposure index, we combined all the indicators related to floods and landslides. We have used the historical data obtained from different agencies (Table 1) to determine the weights of the individual exposure indices. Finally, we created a common exposure index by adding different exposure indices as per Iyengar and Sudarsan method (Coninx & Bachus, 2007; Villordon, 2015). Some indicators have a positive relationship with vulnerability, *i.e.*, the vulnerability increases with the increase in the value of the indicators. On the other hand, some indicators have a negative association with vulnerability. The graphical representation of all the indicators considered under the exposer index is presented in Fig. 6 and Fig. 7.

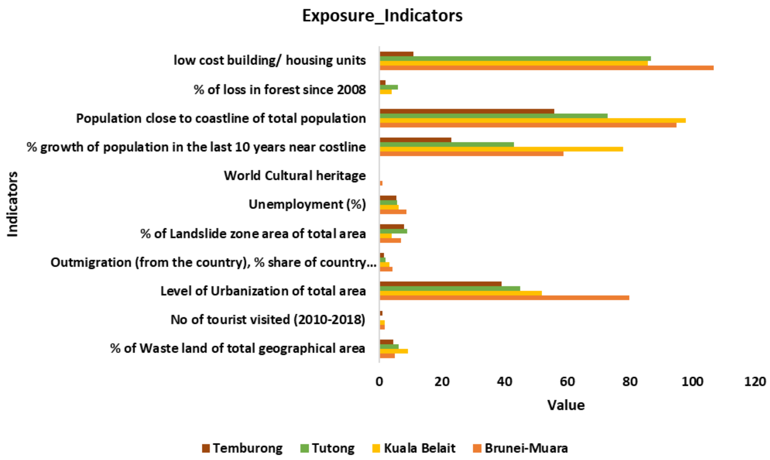


Figure 6. *Different indicators under exposure index*

Along with these indicators, seven indicators under hydrological factors are also chosen to explore the exposure index, as shown in Fig. 8. The rainfall data is available only for the Brunei-Muara district and not for the other districts. For estimation of average monthly rainfall, we used Inverse Distance Weighting (IDW) method (Supharatid, 2015). Since this method can be used to estimate unknown spatial data from known data of sites that are adjacent to an unknown location, we considered a few neighboring areas of Malaysia and interpolated the average rainfall. The IDW method estimates the unknown cell values in the output surface by averaging the values of all input sample data points that lie within the specified search radius (Nyatuame et al., 2014). Daily, monthly or yearly rainfall data for a region with coordinates (Latitude and Longitudes) are the input of the model. The method involves the process of assigning values to unknown points by using values from a set of known locations. The estimated average rainfall pattern of different districts of Brunei Darussalam from 1991 to 2016 has been presented in Fig. 7 (a-d).

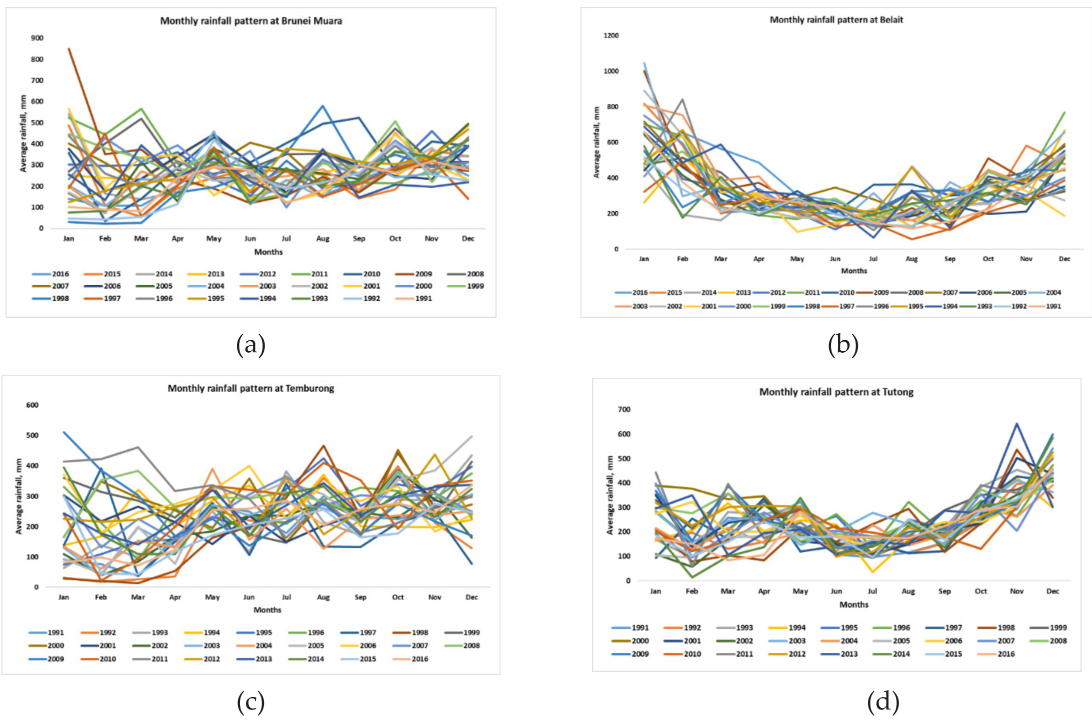


Fig. 7 *(a-d): The monthly average rainfall pattern of a. Brunei-Muara b. Belait c. Tutong d. Temburong*

As per the graph shown in the Fig.7a-d, we can say that the variation of average rainfall is from 600-800 mm in the month of Jan, Feb, Nov, and Dec for all districts except Belait, where the variation is up to 1100 mm. Also, as per the literature review, the heavy rainfall days are considered as the day when rainfall is more than 170 mm(Assessment & Issues, n.d.; Banyouko et al., 2017; Ndah et al., 2016).

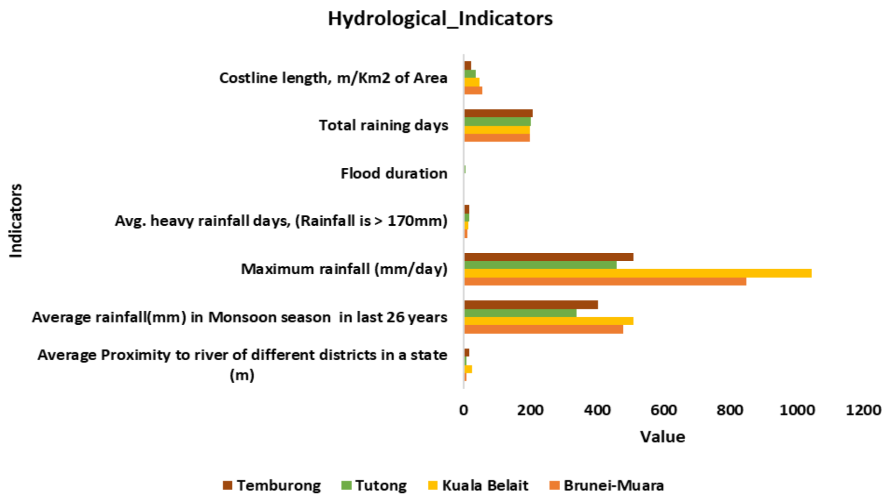
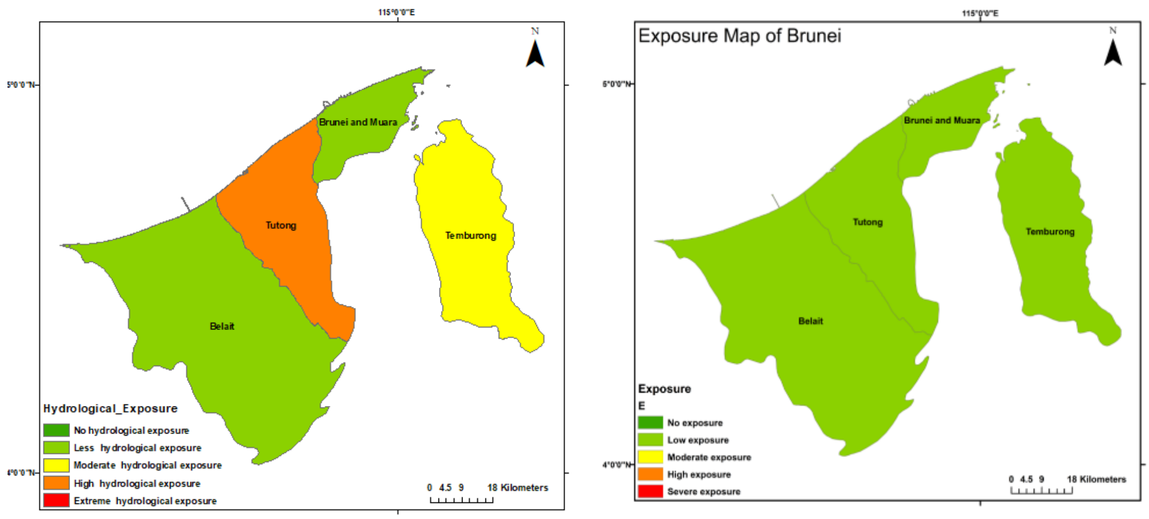


Figure 8. *Hydrological factors under the exposure index.*



a. b.

Figure 9. (a-b): *Showing the exposure map of Brunei Darussalam*

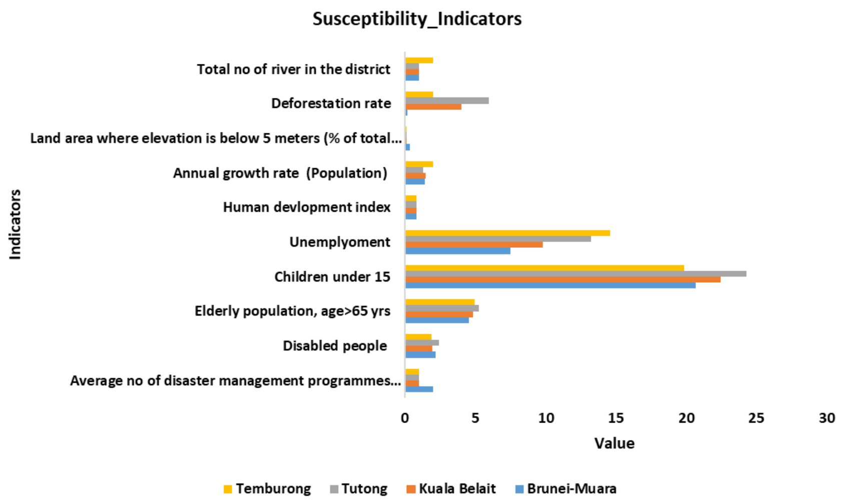
The analysis of the data (Fig. 8) shows that Brunei-Maura has more low-cost buildings, level of urbanization, coastline length, and more population living close to the coastal area in comparison with other districts. In Kuala Belait, the average rainfall and maximum rainfall are high in comparison to other districts of the country. The exposure map of different states of Brunei Darussalm is shown in Fig. 9(a-b). All the four districts of Brunei Darussalm have low exposure (5-10%) towards the vulnerability due to less rate of unemployment, outward migration, and landslide zonation. In the case of hydrological exposure, the Tutong district has high exposure, followed by Temburong, which has moderate hydrological exposure. In the Tutong district, the proximity to the riverside is very less and also, the district is facing the maximum number of rainfall days, along with maximum flood durations. The level of classification of vulnerability components is presented in Table 2 (Chakraborty & Joshi, 2017; Huang et al., 2005; Karmaoui et al., 2016; Kissi et al., 2015).

Table 2. *Vulnerability level classification*

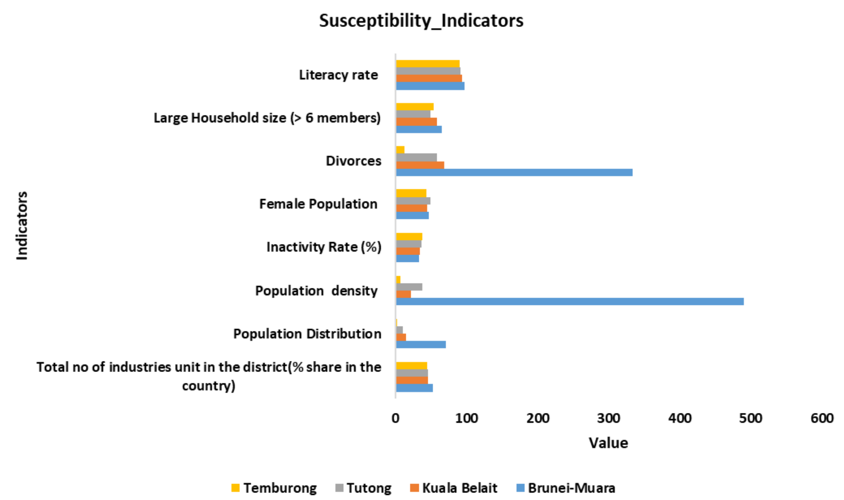
Range of factors (in %)	Level of vulnerability or vulnerability components
<1	No
1-5	Less or low
6-10	Moderate
11-15	High
>15	Extreme or severe

Susceptibility index:

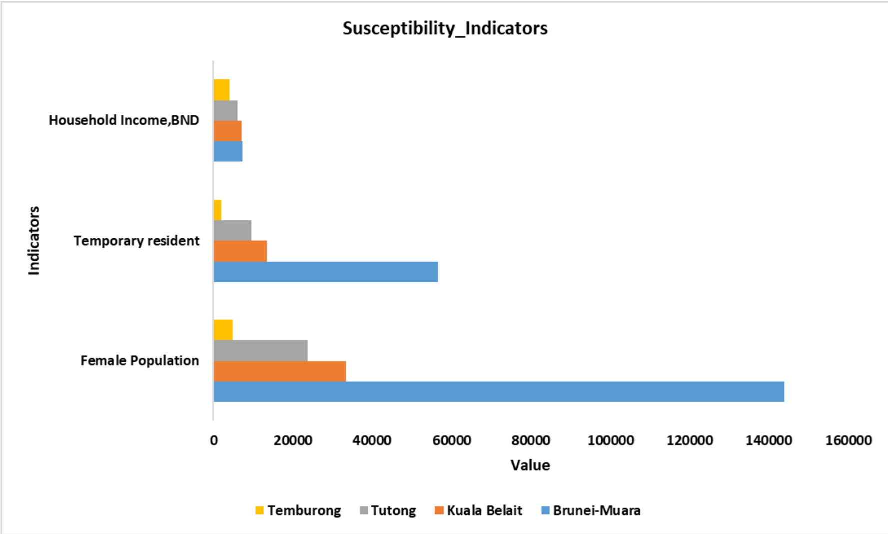
For the present study, twenty-one variables (indicators) were taken into consideration to calculate the district wise susceptibility to flooding. The indicators considered in this study are listed in Table 1, along with their relationship with the susceptibility index. The graphical representation of all these factors is shown in Fig. 10 (a-c).



a.



b.



c.

Figure 10. *(a-c): The different indicators of the Susceptibility index for Brunei districts.*

Brunei-Muara has the highest population density as well as the most female population. Even then, none of the four districts of Brunei Darussalam have high susceptibility towards vulnerability. The main region behind this is that the country has a very good household income, high literacy rate, low annual growth rate, and high human development index, especially in the Brunei-Muara. The susceptibility index is calculated based on these indicators and shown in Fig. 11. The figure shows no susceptibility in Kuala Belait and less susceptibility in the other three districts of the country.

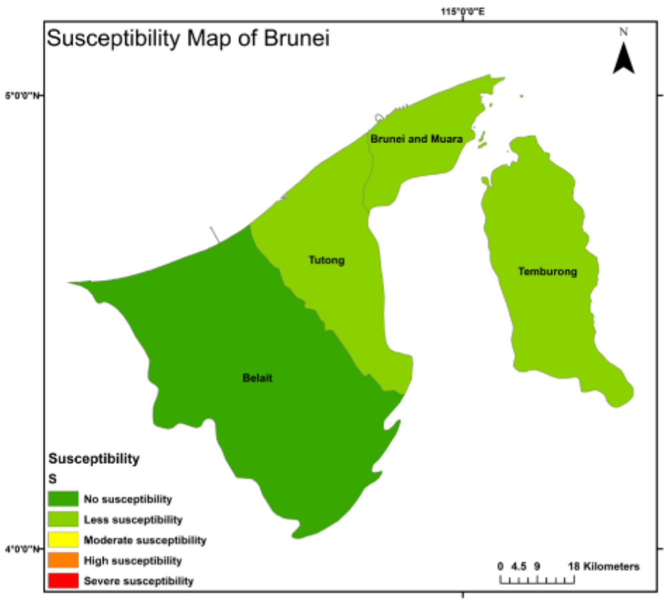
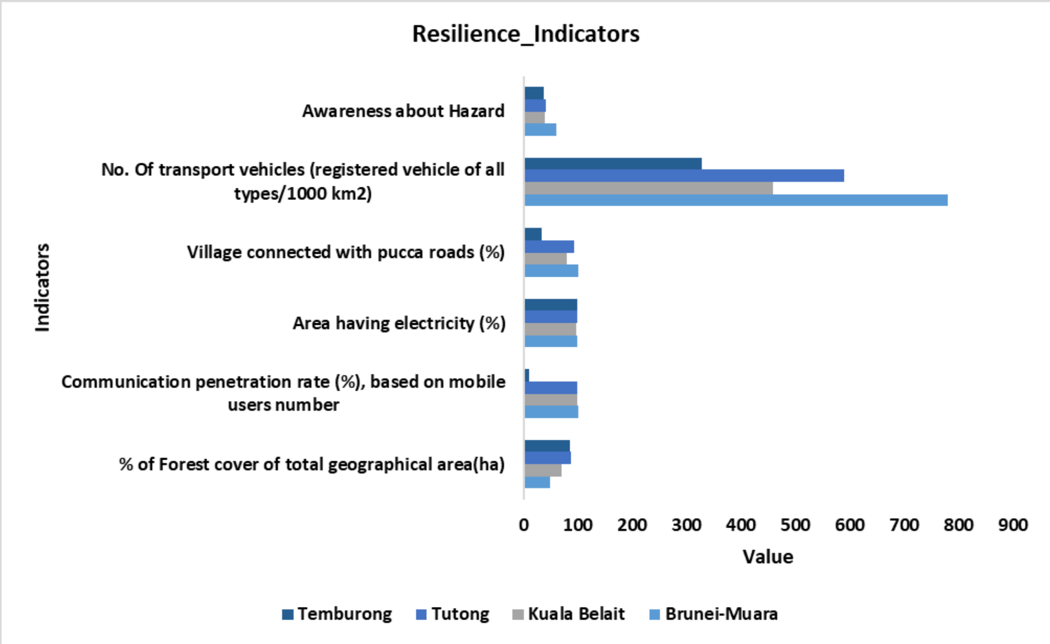


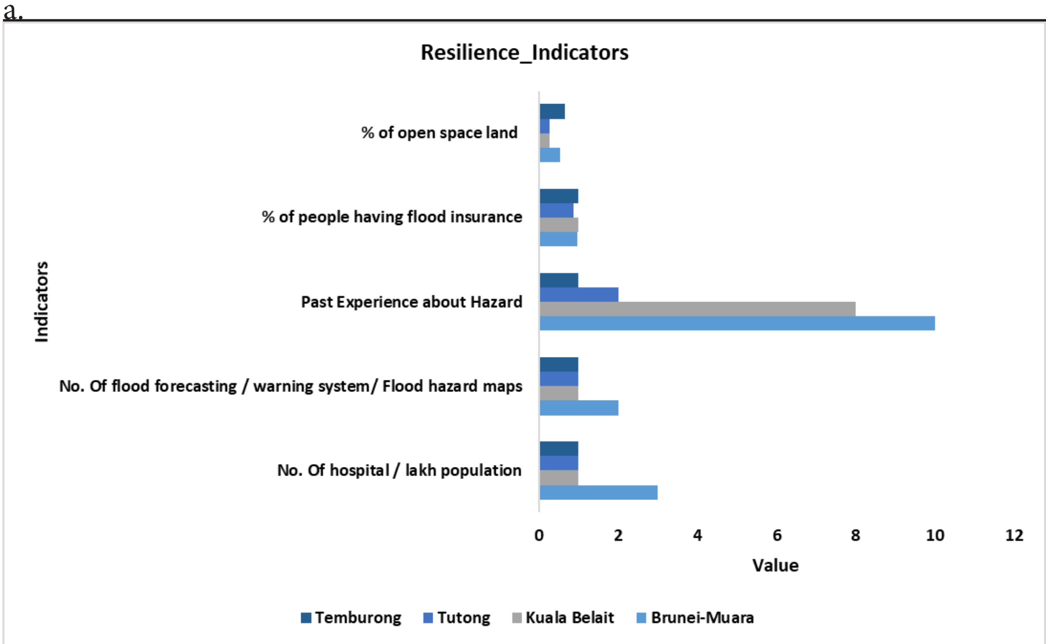
Figure 11. *Showing the susceptibility map of Brunei.*

Resilience index

As explained earlier, the capacity of a social system to counter and overcome any adverse event is called resilience. In the present study, fourteen indicators were taken to examine the district-wise resilience to flood and their impacts in terms of forest cover, communication penetration rate, awareness, and past experience, etc. Fig. 12 (a-b) shows the graphical representation of different resilience factors used in the analysis.



a.



b.

Figure 12. (a-b): *The different indicators of resilience index for Brunei.*

The resilience or resistive factor towards vulnerability like length of road connecting district headquarters, transport vehicle availability, length of canals, and health facilities centers are best available in the Brunei-Muara. Even then, the Kuala Belait has most resilience towards the vulnerability, followed by the Tutong district since the Kuala Belait has maximum forest cover and canalization in comparison with others. In Tutong, the maximum number of the population has experience as well as knowledge about the flood and disaster.

Based on these indicators, the resilience index is calculated and shown in Fig. 13. A comparative bar diagram showing the different indicators of vulnerability in different districts of Brunei Darussalm is presented in Fig. 14.

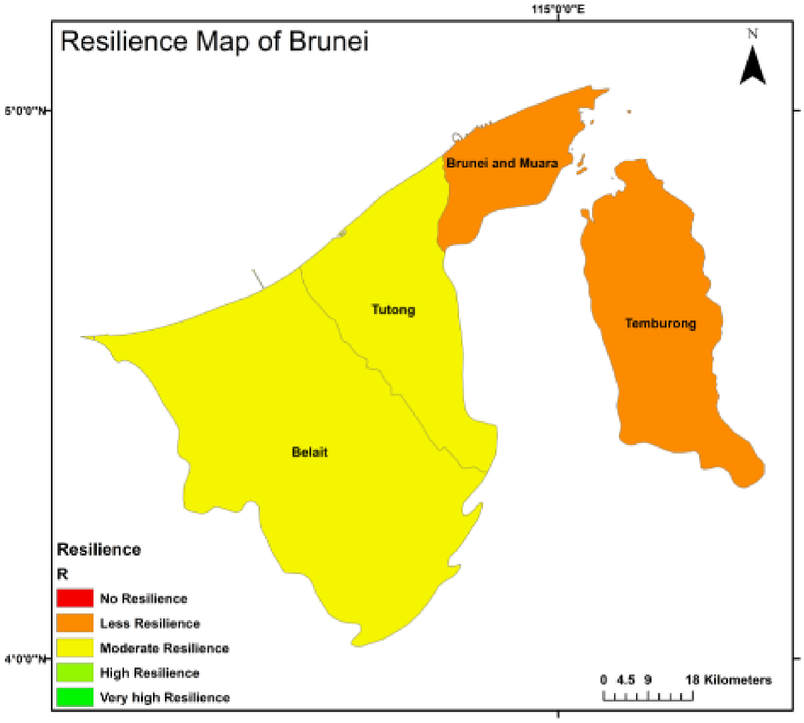
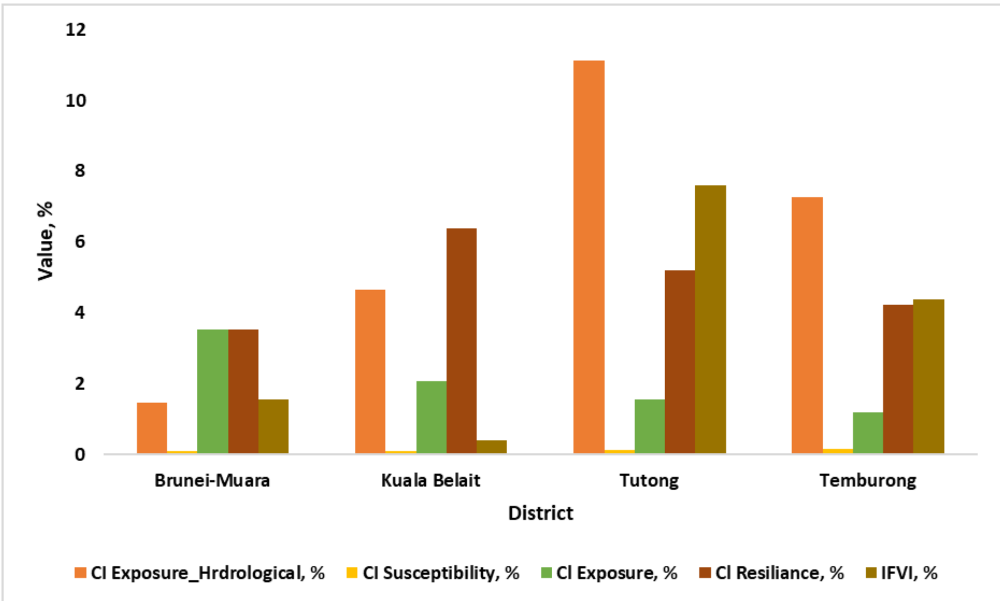


Figure 13. *Showing the resilience map of Brunei.*



1. Figure 14. *Showing all indexes of the vulnerability of different districts of Brunei Darussalam. The impact of different indicators over vulnerability indices: Correlation analysis*

The correlation analysis of different indicators with their corresponding indices *i.e.* between exposure index and the exposure indicators, between susceptibility index and susceptibility indicators and so on, are shown in table 3, 4, and 5, respectively. In case of exposure, the factors like proximity of district to the river, annual growth rate, percentage waste land, and the population distribution range are major factors which are contributing towards the vulnerability. In the case of susceptibility female populations, old age population, and population density make a location more vulnerable. The factors like communication facilities available, connectivity to district headquarters, availability of flood forecasting system, and the number of hospitals, are major resilience factors which reduce the vulnerability of an area.

Table 3. *Relation between different exposure factors and exposure index and the Pearson correlation coefficient (r)*

Factors	Pearson correlation coefficient (r)
CI_Exposure	1.00
% of waste land of total geographical area	0.47
No. of tourist visited	0.36
Forest fire (Total affected area)(ha)	0.41
Urbanized area(%)	0.41
Unemployment(%)	0.78
Proximity to ocean (m)	0.71
Avg. Rainfall of last 50 years in JJA (mm/year)	0.66
Flood frequency(≥ 700 cumec)	0.46

Table 4. *Relation between different Susceptibility factors and susceptibility index and the Pearson correlation coefficient (r)*

Factors	Pearson correlation coefficient (r)
Cl_susceptlibity	1
Population density (Person/Km^2)	0.51
Disabled people (%)	0.17
Elderly (%)	0.39
Children under 15(%)	0.03
Illiteracy rate (%)	0.34
Household size (%)	0.25
Poverty Rate (%)	0.14
Decadal growth rate (%)	0.49
Female Population (%)	0.36

Table 5. *Relation between different Resilience factors and the resilience index and the Pearson correlation coefficient, r.*

Factors	Pearson correlation coefficient (r)
CI_RESILIENCE	1
% Of forest cover (with total GA)	0.17
Road network (km)	0.74
Communication penetration rate (%)	0.81
Area having electricity(%)	0.11
No of hospital / lakh population	0.49
Awareness about hazard	0.13
Past Experience about hazard	0.27

The integrated flood vulnerability index for Brunei Darussalam

After obtaining all the index values of the vulnerability, the integrated flood vulnerability index has been prepared by integrating all index values into Eq. 7, and the final map is prepared by using ArcGIS software. The Tutong district has the highest vulnerability, with 7.5 %, followed by Temburong with 4.3 %. As seen in Fig. 14 and 15, Belait has the lowest vulnerability index, with 0.4 %. Tutong has an inferior communication network in comparison with other districts and also the hospital units, total length road connections, HDI is less as well as the number of the disabled and divorcee person is high in Tutong. Along with this, Tutong is also hydrologically unstable in comparison with the other districts of Brunei Darussalam. Since Brunei Darussalm has a high literacy rate, a very low unemployment rate, 100 % electricity, less populated, and supported by good household income, so no district in the country is under high or extremely vulnerable categories. Only the Tutong district has a moderate vulnerability index.

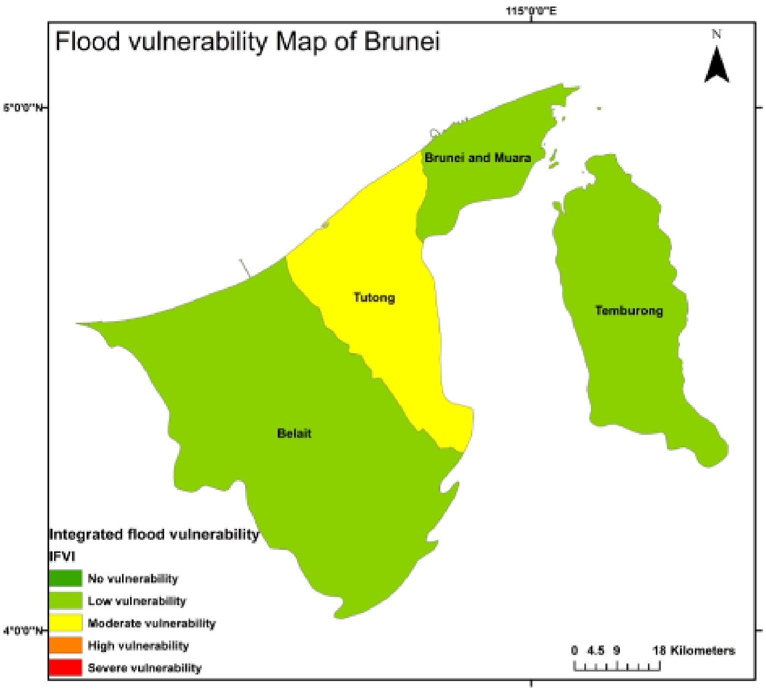


Figure 15. *The integrated flood vulnerability index of different districts of Brunei.*

5. Conclusion

The present study determined the district wise integrated flood vulnerability index for Brunei Darussalam. The important aspect of this study is to assign vulnerability rank to each district according to its vulnerability level relevant to the flood. An integrated approach was adopted where vulnerability is the function of exposure, susceptibility, and resilience. Several indicators have been selected to have an accurate representation of the vulnerability. Since each indicator has a different measurement unit, a normalization procedure was used to convert them into a single value of effective comparison. A significant problem concerning disaster assessment in Brunei Darussalm is the absence of documentation of relatively small chronic hazard events, especially annual floods, flash floods, and landslides, to global disaster databases. Due to a lack of datasets related to these events, it is quite challenging to study the nature and effectiveness of disaster in the country. Perhaps due to the lack of having a comprehensive dataset on related disasters, no extensive study was performed for the vulnerability assessment of Brunei Darussalam. Besides, the hydrological data such as runoff, discharge, depth of groundwater table, and district-wise rainfall data due to lack of rainfall stations in each district is not available in Brunei Darussalam. The present study, based on the data availability and few assumptions such as interpolation of rainfall, is a pioneer effort to establish an integrated flood vulnerability index for Brunei Darussalam. The proposed integrated vulnerability assessment may work as a potential guideline for the center of flood-related policy and management, such as the National Disaster and Management Centre (NDMC) in Brunei Darussalam. The outcome of the present study would be a significant addition to better preparation and perception of disaster risk in Brunei Darussalam. The present study may be helpful to the governmental organization to plan for different mitigation measures to reduce vulnerability.

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